VOLUME 56 NUMBER 6

THE JOURNAL OF GEOLOGY

November 1948

CORRELATION OF PLEISTOCENE DEPOSITS OF THE CENTRAL GREAT PLAINS WITH THE GLACIAL SECTION[1]

JOHN C. FRYE, ADA SWINEFORD, AND A. BYRON LEONARD
State Geological Survey, University of Kansas, Lawrence

ABSTRACT

Integration of Pleistocene chronologies of the central Great Plains and the glaciated area is a major problem of late Cenozoic stratigraphy in North America. Lenticular deposits of volcanic ash associated with fossil mollusks occur in both regions and furnish a widespread datum for interregional correlations. The ash lentils, collectively called Pearlette, can be differentiated petrographically from other late Cenozoic ash deposits of the Plains region and have been studied at localities extending from southeastern South Dakota to northwestern Texas. The associated molluscan fauna possesses an unforeseen degree of uniformity and stratigraphic significance. The Pearlette ash and faunal zone occurs above Kansas till and below Loveland loess and Iowa till in the Missouri Valley region and is judged to be early Yarmouthian in age. A modification of stratigraphic names for Kansas contributes to uniformity of terminology in the Plains region.

INTRODUCTION

The late Cenozoic glacial epoch has left some imprint of its history on virtually every region of the North American continent. The physical changes in the earth and the evolution of faunas during this time have been subjects of detailed study. In some regions, such as those covered by extensive continental ice sheets, the wealth of data recorded by many investigators has led to a detailed chronology and stratigraphic classification that is based primarily on advance and retreat of the various ice sheets.

Nevertheless, in any attempt to review the late Cenozoic history of the continent as a whole, one is immediately confronted with the lack of correlation among four distinct environmental provinces, each of which has its own chronology that is largely unrelated to that of other regions. These provinces are (1) the extensive area covered by the continental ice sheets, containing deposits made by ice and other deposits intercalated between them; (2) extra-glacial areas which were subjected to prolonged erosion during the epoch of successive glaciations, possessing a record that consists primarily of erosion surfaces rather than of sediments; (3) regions of fluvial and eolian deposits where the chronology has been developed largely (*a*) on the basis of fossil vertebrate faunas, as in the central and southern Great Plains, or (*b*) on the basis of an extensive terrace sequence, as in the lower Mississippi Valley region; and (4) areas of the continental margins containing marine deposits which have been differentiated largely on the basis of marine invertebrates.

It is the purpose of this paper to present data which establish a more precise

[1] Manuscript received April 23, 1948.

correlation of the glacial succession of the upper Mississippi Valley with fluvial and eolian strata of the central and southern Great Plains.

During the past decade and a half, detailed field studies and investigations of fossil vertebrate faunas have been made in Kansas and Nebraska. As a result of these studies in Kansas, large areas and considerable thicknesses of deposits formerly thought to be Pliocene in age and loosely classed as belonging to the Ogallala formation have been assigned definitely or tentatively to Pleistocene time. A review of the literature is not presented here but may be found for Iowa in Kay and Apfel (1928) and Kay and Graham (1943); for Nebraska in Lugn (1935), Condra, Reed, and Gordon (1947), and Schultz and Stout (1945; 1948, in press); for Texas in Evans and Meade (1945) and Meade (1945); and for Kansas in Frye (1945*a*, 1946). Although a usable scheme of chronology, based on stratigraphic and physiographic relations and fossil vertebrates, has evolved in the Plains region, the lack of adequate vertebrate faunas in deposits of the glaciated areas has prevented integration of this chronology with that of the glacial succession in the north-central United States, which has been accepted by many geologists as the standard Pleistocene record for North America. This lack of correlation with the glacial time scale has retarded clear understanding of Pleistocene chronology and stratigraphy in the Great Plains.

A step toward integration of the geologic record in the two provinces was taken when a buried soil zone that is part of the glacial series was traced from Iowa, South Dakota, and Nebraska southwestward into central Kansas (Lugn, 1935; Schultz and Stout, 1945, p. 241; 1948; Condra, Reed, and Gordon, 1947; Frye and Fent, 1947). This soil, which occurs at the top of the Loveland loess, establishes a key horizon of late Pleistocene age but still does not serve needs adequately because it is near the top of the succession of Pleistocene strata, and in some topographic situations it is subject to possible confusion with other buried soil zones.

A more important step toward integration of data representing the two provinces has been made possible by discovery of the widespread occurrence of distinctive deposits of volcanic ash within the late Cenozoic sediments of the Great Plains. In 1896 Cragin applied the name Pearlette to a volcanic ash lentil along Crooked Creek Valley in Meade County, Kansas. Similar deposits, some attaining a maximum thickness of more

PLATE 1

Pearlette volcanic ash bed in Iowa, Texas, and Kansas.

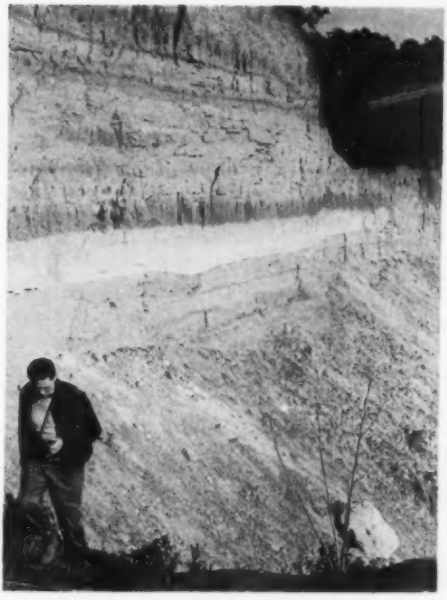
A, Exposure in gravel pit along the Missouri Valley bluff near Little Sioux, Iowa (loc. no. 3). Deposits classed by Iowa Geological Survey as Loveland sand and gravel at base (Grand Island member of Meade formation, Kansas classification), stratified sand, silt, and volcanic ash (Sappa member of Meade formation, Kansas classification), and Loveland loess with soil at top. Peorian loess occurs above the Loveland soil.

B, View at same locality as *A*, showing detail of Pearlette volcanic ash in stratified sand and silt and at top the supposed unconformity at base of Loveland loess.

C, Detail of slightly indurated Pearlette volcanic ash which caps a small mesa west of Channing, Texas (loc. no. 46).

D, Meade formation in Gove County, Kansas (loc. no. 20). Base of Pearlette volcanic ash at hammer; beds in foreground yielded abundant snail fauna and consist predominantly of fragments of Niobrara chalk which immediately underlies the Mead formation at this locality.

A



B

C

D

A

B

C

D

than 20 feet, have been described from widely scattered localities in western Kansas (Landes, 1928), Nebraska (Lugn, 1935; Schultz and Stout, 1945, pp. 237–240), and Oklahoma, where volcanic ash has been mined commercially at many places (pl. 2). Most early workers in Kansas considered the ash to be Pliocene in age. Cragin's Pearlette lentil, however, occurs within the type area of the Meade formation, which has yielded several distinctive Pleistocene fossil vertebrate faunas (Hibbard, 1944).

Volcanic ash is also known to be interbedded with glacial deposits of the Missouri Valley region of South Dakota, Nebraska, and Iowa (Todd, 1892, 1895, 1899; Kay and Graham, 1944, p. 85; Schultz and Stout, 1945, p. 238; Condra, Reed, and Gordon, 1947, pp. 22–23). If there were means for distinguishing individual ash falls of different age, these lentils might serve as means of correlating deposits across the glacial border. The value of the ash lentils for correlation purposes is greatly increased by the association with them of both vertebrate and invertebrate fossil faunas.

In order to determine the distinctiveness of the several falls of ash, a petrographic and chemical study was made of volcanic ash deposits in western Kansas and adjacent states (Swineford and Frye, 1946) that had been approximately dated by vertebrate fossils and other methods. It was found that each of the several ash falls studied in the Great Plains possesses distinctive petrographic characters, and thus volcanic ash beds can be used for regional correlations.

During the summer of 1947 we examined in the field outcrops of the supposed Pleistocene volcanic ash throughout a belt extending from the Missouri Valley area of Iowa and Nebraska southwestward across Kansas and western Oklahoma to the described localities (Sidwell and Bronaugh, 1946) of northwestern and west-central Texas (pl. 1, *C*). Progress of field work was greatly facilitated by the active co-operation given to us by the state geological surveys of Iowa, South Dakota, Nebraska, and Oklahoma and the University of Nebraska State Museum. Dr. Raymond Sidwell, Texas Technological College, Lubbock, Texas, furnished us with samples of Pleistocene volcanic ash from localities in western Texas. Many of the localities in central and western Kansas had been studied prior to 1947, some of them in co-operation with Dr. C. W. Hibbard, formerly curator of vertebrate paleontology at the University of Kansas Museum of Natural History, and various members of the staffs of the state and federal geological surveys working in Kansas.

PLATE 2

Pearlette volcanic ash bed in Kansas, Oklahoma, and Nebraska.

A, Pearlette volcanic ash and thin overburden exposed in pit operated by Mid-Co Products Company south of Meade, Meade County, Kansas (loc. no. 36). This pit is in the vicinity of Cragin's type locality of the Pearlette ash. Snail fauna was collected from the clays below the ash and exposed in the floor of the pit.

B, Pearlette volcanic ash exposed in commercial pit north of Gate, Oklahoma (loc. no. 38). Snail fauna collected from clay exposed below the ash in near-by gullies. A pronounced north dip of the Pleistocene beds is due to solution-subsidence of the underlying Permian rocks.

C, Pearlette volcanic ash and underlying silty clay exposed in abandoned pit of the Cudahy Packing Company, near Orleans, Nebraska (loc. no. 9).

D, Same locality as *C*, showing Sappa (Upland), Loveland, and Peorian formations (Nebraska classification) exposed above the Pearlette volcanic ash.

Our field work was aided by two field conferences held during the summer of 1947. In May members of the state geological surveys and state universities of Iowa, Nebraska, and Kansas met in the field to study Pleistocene deposits exposed in western Iowa north of Council Bluffs, particularly at Loveland and near Little Sioux, and in the adjacent part of Nebraska. In June a regional field conference designed to study the stratigraphy of late Pleistocene deposits, particularly the loesses, convened at Peoria, Illinois, and worked westward across Illinois, Iowa, South Dakota, and Nebraska. This conference was attended by representatives of the state geological surveys of Illinois, Iowa, South Dakota, Nebraska, and Kansas, the University of Nebraska State Museum, the Soil Survey of the United States Department of Agriculture, and the Geological Survey of the United States Department of Interior.

Samples of ash were collected in the field from surface exposures by use of shovel, pick, and, in some cases, hand auger. The molluscan fauna, where present, typically occurs within the first few feet of sediments below the base of the ash (pl. 1, *D*) or, rarely, disseminated through the ash or immediately above it. Only those localities where the field relationships were clear have been included in this study. The sampling of the ash for an earlier study (Swineford and Frye, 1946) was quite thorough; many of the deposits were both channeled and spot sampled and the uniformity of petrographic and chemical characters demonstrated. Therefore, the sampling for this study consisted of the collection of one spot sample from a pure and unweathered portion of the ash lentil. All localities reported in table 1 and figure 1 were sampled by us except localities 4, 5, 21, 26, and 50. Locality 4 was sampled by A. G. Unklesbay of the Iowa Geological Survey, locality 5 by E. C. Reed of the Nebraska Geological Survey, locality 21 by Norman Plummer of the State Geological Survey of Kansas, locality 26 by A. C. Carpenter of Ottawa, Kansas, and locality 50 by Laura Lu Tolsted. In the field large sacks were filled with fossiliferous sediments; later, in the laboratory, the shells were separated from their matrix by washing the sediments through screens.

PEARLETTE ASH ZONE IN THE GLACIAL SECTION

It is desirable, first, to establish the stratigraphic position of the Pearlette ash zone in the glacial succession of the Missouri Valley area. In 1924 Kay (p. 73) wrote concerning the well-known deposits of volcanic ash northwest of Little Sioux, Harrison County, Iowa: "The writer is convinced that this volcanic ash is not of Aftonian age, but is of the same age as the Loveland loess, with which in some of the county line exposures it is interstratified." In 1943 Kay and Graham (p. 85), in a paper on the Illinoian and post-Illinoian Pleistocene geology of Iowa, stated:

> The ash in the Little Sioux area is in the lower part of a loess phase of the Loveland formation, or may be associated with Loveland silts and clays showing deposition in water, but changing gradually into the typical eolian loess phase of the overlying Loveland. Frequently, sections of the Loveland which include the volcanic ash indicate that the pumicite was deposited in shallow ponds, lakes or bayous after the sands and gravels of the Loveland age had been deposited.

In 1947 Condra, Reed, and Gordon (p. 22) classed the Pearlette ash as a separate formation occurring conformably above the Upland[2] silty clay and the

[2] The Nebraska Geological Survey is now using the name Sappa to designate the deposits formerly

Grand Island sand and gravel (which constitute the lower part of the Loveland formation of Kay and Apfel and of Kay and Graham) and below the Crete sands and gravels and Loveland loess. During the field conference of May, 1947, the Pleistocene deposits exposed at the Loveland type section and in the vicinity of Little Sioux (pl. 1, *A* and *B*) were critically re-examined. It was agreed by the members of the conference that at the Little Sioux locality (1) thick stream-deposited sands and gravels occupy a deep erosional channel cut into glacial till of probable Kansan age; (2) these sands and gravels grade upward into stratified silts and sands that include the volcanic ash and associated snail fauna in its upper part; (3) laterally the channel gravels become thinner and the bedded sandy silts rest directly on glacial till; and (4) the bedded silts are overlain by two loess sheets, which are properly classed as Loveland and Peorian. The evidence in the Little Sioux area is less conclusive, however, as to the existence of an important unconformity at the top of the bedded silts that include the volcanic ash (Sappa) and the presence locally of thin channel deposits of sand and gravel (Crete) above the unconformity and below the Loveland loess.

The volcanic ash in Ringgold County, Iowa (loc. 4), is considered by members of the Iowa Geological Survey to occur above Kansas till, which in turn overlies Nebraska till, but relationships of the ash to the overlying beds are not clear.

Northward along the Missouri Valley, localities 1, 2, 5, and 6 are of considerable importance in establishing the placement of the ash zone, since at each of these localities either the ash lentils, the snail fauna, or both occur below a younger glacial till. At locality 2, in extreme northwestern Iowa, the volcanic ash was not found, but a large and distinctive snail fauna that is ascertained to be of contemporaneous age was collected from sediments stratigraphically above till sheets thought to be Nebraskan and Kansan in age and below Loveland loess, Iowa till, and Iowa loess. It should be noted that, although these localities all lie beyond the limits of the Iowa till as formerly mapped, they are well within the area shown by recent studies to have been covered by Iowan ice (Smith and Riecken, 1947; Flint, 1947; Warren, 1947; H. E. Simpson, 1947).

At locality 1 near Hartford, South Dakota, a thin lentil of volcanic ash occurs in a section of tills, loesses, and lenticular sand and gravel. The ash occurs above a small channel fill of sand and gravel resting unconformably on glacial till. Laterally, sand and gravel pinch out and the ash rests directly on weathered till. The ash is overlain by stratified silt and sand and Loveland loess; the latter displays a leached zone more than 1½ feet thick below unleached Iowa till. Iowa loess overlies the Iowa till. Dr. R. F. Flint, who is conducting a detailed investigation of the glacial deposits of South Dakota for the United States Geological Survey, was a member of the field conference when this section was examined and sampled.

At locality 5 in Knox County, Nebraska, the volcanic ash and associated snail fauna occur in stratified sand, silt, and clay (Sappa formation) that lie conformably on sand and gravel (Grand Island formation) which, in turn, rests on eroded Pierre shale. The beds containing the ash are overlain by Iowa till (per-

called Upland (personal communication from E. C. Reed, dated March 23, 1948), and throughout this paper the name Sappa will be applied to beds called Upland in earlier literature.

sonal communication from E. C. Reed). At locality 6, in Cedar County, Nebraska, volcanic ash occurs stratigraphically above Kansas(?) till and below Iowa till.

These data serve to establish the stratigraphic placement of the Pearlette volcanic ash and its associated molluscan fauna in the Missouri Valley region. The deposits containing the ash and fauna are shown to be younger than glacial till, judged to be of Kansan age, but older than Loveland loess and overlying glacial till of Iowan age. Furthermore, prior to the deposition of the ash, the Kansas till was dissected by streams, and the valleys thus carved were deeply alluviated. Accordingly, the ash cannot belong to an age older than the Yarmouthian interglacial interval.

Placement of the ash with respect to the time of the Illinoian ice sheet, which advanced between Kansan and Iowan glaciations, is uncertain, largely owing to the lack of conclusive evidence concerning both the eastward correlation of the Missouri Valley Loveland loess and the presence of an erosional unconformity between the stratified beds containing the ash (Sappa) and the overlying Loveland loess. The problem of eastward correlation of the Loveland has been discussed by Kay and Graham (1943, pp. 47–49) as follows:

> Within the Illinoian drift area there are, in many places, two loesses on the Illinoian gumbotil and on surfaces of Illinoian drift. The younger of these two loesses is the Peorian loess; the older loess has been named in Illinois the late Sangamon loess. In Iowa this older loess has been correlated by Kay with the widespread Loveland loess of western Iowa, which is later than Kansan gumbotil erosion and is pre-Iowan in age. Leverett, however, correlated the Loveland loess of western Iowa with pre-Illinoian loess and questions the existence of a post-Illinoian, pre-Peorian loess. But in recent years this older loess on the Illinoian has been mapped widely by members of the Illinois and Iowa Geological Surveys. Although the Loveland loess of western, central, and southern Iowa outside the limits of the Illinoian area appears to be a single formation which was deposited in post-Illinoian, pre-Iowan time, Kay has stated that in reality its lower part may be pre-Illinoian in age, and only its upper part post-Illinoian; and it may be that a part of the Loveland loess in western Iowa and adjacent areas was deposited during the Illinoian glacial age.

In the Missouri Valley localities studied by us, a leached zone as much as 2 feet thick occurs in the top of the Loveland loess below unleached Iowa till, which suggests that even the upper part of the Loveland in this area cannot be considered younger than early Sangamonian. Furthermore, evidence from several localities (Condra, Reed, and Gordon, 1947, p. 24) indicates the presence of an unconformity between the Sappa formation of Nebraska and the Crete and Loveland formations of that area, even though this relationship is not clearly shown in the Little Sioux, Iowa, locality. We express our judgment that the weight of available evidence supports assignment of the Pearlette zone to the early part of the Yarmouthian interglacial age.

METHODS OF CORRELATION

A detailed classification of Pleistocene time, based on the advance and retreat of the several ice sheets, has been in use for many years in the glaciated region. Lately, a usable but less detailed chronology has been developed in the Great Plains region, based primarily on fossil vertebrates, stratigraphic succession, and paleophysiography.

As already noted, relatively few vertebrate remains are found in the glaciated region, and thus vertebrate paleontological studies cannot be applied successfully to correlations of the glaciated and non-

glaciated areas. Stratigraphic succession, which is very useful in local areas, is not very helpful in regional studies, particularly where deposits of distinctive lithologic character, such as glacial till and buried soils, are lacking. Paleophysiography is a valuable tool in the study of fluviatile sediments, particularly in the Great Plains region, where major drainage changes have occurred, but, if work of this sort is to be wholly reliable, detailed knowledge of the entire drainage basin is required.

Two hitherto little-known tools for Pleistocene correlation have been used extensively in this study—the distinctive petrographic and chemical characteristics of volcanic ash beds and the composition of fossil snail faunas found to be widely distributed in association with ash deposits. Use of these tools will be described.

PETROGRAPHY OF THE PEARLETTE VOLCANIC ASH

Samples of volcanic ash determined to represent the same fall as Cragin's Pearlette ash of southwestern Kansas were collected from forty-eight localities (fig. 1). The locations, occurrence, and petrographic data are given in table 1, and chemical analyses are given in table 2. The methods of petrographic study employed in the present investigation are essentially the same as have been described (Swineford and Frye, 1946) in previous work on Great Plains volcanic ash deposits. The laboratory procedures and distinctive characteristics of the ash are outlined briefly below. As the volcanic ash of the region is of the vitreous type, no mineralogical analyses are included.

Laboratory procedure.—Where several samples of volcanic ash were taken from one locality, the analytical results were reported for the sample which was the freshest and the least contaminated. The samples were dried and separated into the following size fractions for analysis: larger than 175 μ, 175–125, 125–88, 88–62, and smaller than 62 μ. Mechanical analyses were not made because previous determinations of particle-size distributions showed no significant pattern. In making the chemical analyses, portions of the 88–62 μ fraction were used, because this fraction in most samples was found to be relatively free from impurities and aggregates. The percentage of iron oxide, which was previously found to have diagnostic value, is reported in the petrographic table as well as in the table of chemical analyses. Megascopic color determinations of the portion passing the 62-μ screen were made by comparison with the Ridgway (1912) color plates.

The degree of alteration was studied (in the 175–88-μ fractions) by use of both the binocular and the petrographic microscopes. Particular note was made of the surface textures of the shards, the presence or absence of anisotropic boundaries which might interfere with refractive-index determination, the relative abundance of polarizing particles and inclusions, and the quantity of cemented aggregates resulting from decomposition.

Particle shape was studied (175–88 μ) by use of a binocular microscope. Note was made of the relative thickness of the glass, the curvature of the bubble walls, the shape and number of junctures between bubbles, and the presence or absence of fibrous shards. Vesicles were noted under the petrographic microscope. Contaminants were studied under both microscopes and were reported for the 175–88-μ fractions. Refractive indices were determined by the immersion method with central illumination, using liquids at intervals of 0.002 and correcting for changes in temperature.

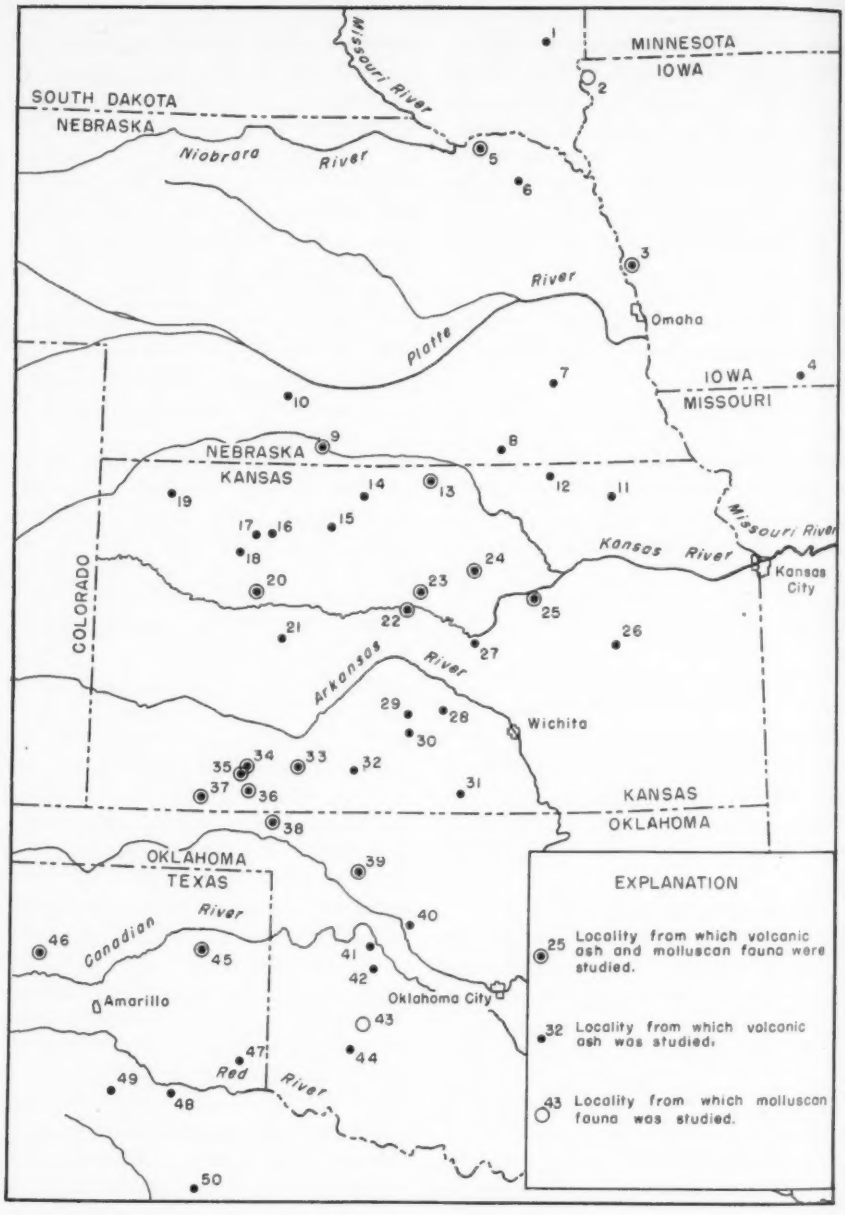


FIG. 1.—Map showing geographic distribution of the Pearlette volcanic ash and associated fossil snail localities studied. The numbered localities are listed in table 1.

TABLE 1

VOLCANIC ASH LOCALITIES STUDIED AND SIGNIFICANT PETROGRAPHIC CHARACTERISTICS OF THE VOLCANIC ASH SAMPLES

No.	Location	Stratigraphic Position	Fauna	Color* (<62μ)	Refractive Index	Per Cent Fe_2O_3	Specific Gravity	Curved Junctures	Long Vesicles	Fibrous Shards	Alteration	Impurities
				South Dakota								
1....	Cen. NW. Sec. 13, T. 102 N., R. 51 W., Minnehaha Co.	0.8 ft. ash, sample bottom 0.2; above Kan. till; below Lvld. loess & Iowa till	.....	17‴ff	1.499–1.501	1.73	2.31	c†	c	r†	Some crystalline inclusions	Tr. qtz. sd.
				Iowa								
3....	Sec. 6, T. 81 N., R. 44 W., Harrison Co.	1.5 ft. ash, sample bottom 1 ft.; within waterlaid sd. & silt; above till; below Lvld. & Peorian loess	Snails below ash	17‴ff	1.499–1.501	1.96	2.28	c	c	c	None	Tr. qtz. sd.
4....	SE. Sec. 18, T. 68 N., R. 28 W., Ringgold Co.	1.5 ft. ash, road ditch, above brown clay & Kan. till; below loess	.....	17‴ff	1.499–1.501	1.98	.....	c	c	r	Some crystalline inclusions; dull surfaces	Tr. qtz. sd.
				Nebraska								
5....	CN1 NW. Sec. 34, T. 33 N., R. 4 W., Knox Co.	Ash in stratified sd., silt, & clay; below Iowa till; above sd. & gr., above Pierre shale	Snails below ash	19‴d	1.499–1.501	.....	.....	c	vc†	c	Many aggregates ($CaCO_3$); grain outlines somewhat anisotropic	5% buff qtz. silt & sd.
6....	NE. Sec. 11, T. 29 N., R. 1 E., Cedar Co.	2.5 ft. ash, in silt & sd.; above Kan. till; below Iowa till	.....	16‴ff	1.499–1.501	1.68	2.33	c	vc	vc	None	<1% qtz. sd.
7....	400 ft. SW. of cen. Sec. 26, T. 9 N., R. 2 E., Seward Co.	6 ft. ash, sample 3 ft. above base; in sdy., silty clay; above sd. & gr.	.....	17‴g	1.499–1.501	1.81	2.23	c	vc	c	None	Tr. qtz. sd.
8....	2 mi. S., 0.1 mi. E., U.S. Hwy., Blue River bridge, Hebron	2 ft. ash, road ditch; above gray, sdy. silt	.....	17‴f	1.499–1.501	1.84	.....	c	r	vr†	Many crystalline inclusions; some anisotropic shard outlines; dull surfaces	Tr. qtz. sd.
9....	SE. Sec. 11, T. 2 N., R. 20 W., Harlan Co.	8 ft. ash, sample 1 ft. above base; in sd. & silt; below Lvld. & Peorian loess	Snails above ash	17‴g	1.499–1.501	1.62	2.17	c	c	c	Aggregates, 90%	2–14% qtz. sd.
10....	S. ½ NW. Sec. 20, T. 8 N., R. 24 W., Frontier Co.	>30 ft. ash; below Lvld. & Peorian loess	.....	17‴f	1.498–1.501	2.08	2.25	c	vc	c	None	Tr. qtz. sd.
				Kansas								
11....	NE. Sec. 11, T. 4 S., R. 9 E., Marshall Co.	2.5 ft. ash, sample 2 ft. above base; creek bank, above gr., sd., & silt; below colluvium	.....	18‴f	1.499–1.501	1.74	.....	vc	c	r	Aggregates, 95%; many crystalline inclusions; dull surfaces	Tr. qtz. sd.
12....	NW. cor. Sec. 20, T. 1 S., R. 3 E., Washington Co.	1 ft. ash, above fn. sd. & silt; below red sd.	.....	17‴f	1.499–1.501	1.61	2.34	vc	c	vr	A few aggregates; some crystalline inclusions	None
13....	CN1 SW. Sec. 33, T. 1 S., R. 9 W., Jewell Co.	3 ft. ash; above 3 ft. crs. to fn. sd.; above Niobrara chalk	Snails below ash	17‴f	1.499–1.501	.....	2.27	c	vc	c	None	Cretaceous foraminifers
14....	NW. Sec. 31, T. 3 S., R. 15 W., Smith Co.	>6 ft. ash, abd. creek meander	.....	17‴f	1.499–1.501	.....	2.29	c	c	c	None	None
15....	SW. Sec. 18, T. 7 S., R. 18 W., Rooks Co.	10 ft. ash, sample 5 ft. above base; above silt, sd., & gr.; above Niobrara chalk	.....	17‴g	1.499–1.501	1.38	2.30	c	vc	c	None	Tr. qtz. sd.

* Color notations adapted from Ridgway (1912).

† vc, very common; c, common; r, rare; vr, very rare.

TABLE 1—*Continued*

No.	Location	Stratigraphic Position	Fauna	Color* (<62μ)	Refractive Index	Per Cent Fe_2O_3	Specific Gravity	Curved Junctures	Long Vesicles	Fibrous Shards	Alteration	Impurities
	Kansas—(*Continued*)											
16....	Cen. W. side Sec. 11, T. 8 S., R. 25 W., Graham Co.	9 ft. ash, abd. pit; above fn. sd.	.....	17'''f	1.499–1.501	.....	2.26	c	vc	vc	A few crystalline inclusions	None
17....	S. ½ Sec. 12, T. 8 S., R. 27 W., Sheridan Co.	3 ft. ash, abd. pit, above sdy. silt, crs. gr., above Ogallala	.....	17'''ff	1.499–1.501	1.93	.....	c	vc	c	Several aggregates; many crystalline inclusions	None
18....	NW. Sec. 34, T. 8 S., R. 28 W., Sheridan Co.	16 ft. ash, abd. pit; sample 3 ft. above base; above silt & sd., below massive silt	.....	17'''g	1.499–1.501	1.84	2.26	c	vc	c	None	None
19....	SW. Sec. 14, T. 3 S., R. 35 W., Rawlins Co.	10 ft. ash in gully, sample 3 ft. above base; above fn. sd., below silt	.....	17'''ff	1.499–1.501	1.44	2.27	c	c	c	None	None
20....	NE. SW. Sec. 21, T. 13 S., R. 26 W., Gove Co.	13 ft. ash, sample 5 ft. above base; above 6 ft. silt, sd., & gr.; above Niobrara chalk	Snails below ash	17'''ff	1.499–1.501	1.93	2.25	c	c	c	None	None
21....	S. ½ NW. Sec. 30, T. 18 S., R. 23 W., Ness Co.	>6 ft. ash overlain by silt	.....	17'''f	1.499–1.501	1.47	2.32	c	c	c	None	None
22....	W. line SE. Sec. 35, T. 14 S., R. 11 W., Russell Co.	0.7 ft. ash, road cut, sample from top 0.2; ash in stratified silt, sd., & gr.	Snails below ash	17'''ff	1.499–1.501	1.18	2.32	vc	c	c	A few aggregates	Tr. qtz. sd.
23....	Sec. 28, T. 13 S., R. 10 W., Lincoln Co.	7 ft. ash, sample 2–5 ft. above base; in stratified silt, sd., & gr.; below silt	Snails below ash	17'''g	1.499–1.501	1.82	2.32	c	c	c	None	Tr. qtz. sd.
24....	NE. NW. Sec. 29, T. 10 S., R. 5 W., Ottawa Co.	6 ft. ash, sample middle 1 ft.; above 3 ft. silt & clay; below 2 ft. silt, sd., & gr.	Snails below ash	17'''g	1.499–1.502	1.54	.....	c	r	r	Many crystalline inclusions; dull surfaces	None
25....	SW. Sec. 35, T. 15 S., R 2 E., Dickinson Co.	1 ft. ash; in silty clay; above & below sd., gr., & congl.	Snails above and below ash	17'''f	1.499–1.502	1.73	2.21	c	vc	c	Crystalline inclusions, a few aggregates, and slightly dull surfaces	Tr. qtz. sd.
26....	Cor. Sixth & West Sts., Emporia, Lyon Co.	0.4 ft. ash, auger hole, 40 ft. below surface; below silt & clay & above sd. & gr.	.....	17'''f	1.499–1.502	.....	.....	c	c	c	Some crystalline inclusions; a few anisotropic boundaries; >50% aggregates	Tr. qtz. sd.
27....	NW. SW. Sec. 15, T. 18 S., R. 4 W., McPherson Co.	6 ft. ash, pit sample 2–4 ft. above base; in stratified sd. & silt; above sd. & gr.; below Lvld. silt	.....	17'''g	1.499–1.501	.....	.....	c	c	c	None	None
28....	NW. cor. SW. Sec. 14, T. 25 S., R. 8 W., Reno Co.	10 ft. ash, sample 3 ft. above base; above silt, sd., & peat; below silt, sd., & gr.	.....	17'''f	1.499–1.501	.....	2.31	c	c	c	Some slightly anisotropic shard boundaries	None
29....	NE. SW. Sec. 28, T. 25 S., R. 11 W., Stafford Co.	2 ft. ash, auger hole in dune depression, sample 1 ft. above base; above gray clay, silt, & sd.	.....	17'''ff	1.499–1.501	1.91	2.21	vc	c	c	None	Tr. qtz. sd.
30....	¼ mi. E. of SE. cor. Sec. 23, T. 27 S., R. 11 W., Pratt Co.	2.5 ft. ash, sample 1.5 ft. above base; above silt, sd., & gr.; below silt	.....	17'''f	?	.....	.....	c	?	vc	Shards notably anisotropic; very dull surfaces	None
31....	NE. cor. Sec. 29, T. 33 S., R. 6 W., Harper Co.	>6 ft. ash, abd. pit, sample 2 ft. above base; above silt & sdy. silt	.....	17'''f	1.499–1.501	2.39	.....	r	c	c	Many crystalline inclusions; 95% aggregates	Qtz. sd., red silt
32....	Cen. W. ½ Sec. 7, T. 31 S., R. 17 W., Comanche Co.	8 ft. ash, sample 6 ft. above base; gray, sdy. silt & clay	.....	16'''ff	1.499–1.502	1.57	.....	r	c	c	A few aggregates; shard surfaces slightly dull	Tr. qtz. sd.
33....	Sec. 13, T. 30 S., R. 23 W., Clark Co.	4 ft. ash, sample 2 ft. above base; above sdy. silt & sdy. gr.; below massive silt	Snails below ash	17'''ff	1.499–1.502	1.96	2.32	c	c	vc	None	Tr. qtz. sd.
34....	Sec. 2, T. 31 S., R. 28 W., Meade Co.	17 ft. ash, pit sample, channel 7–9 ft. from base; above clay & sd.; below silt	Snails below ash	17'''ff	1.499–1.501	1.67	2.27	c	c	c	Surfaces slightly dull	None
35....	SE. SE. Sec. 33, T. 31 S., R. 28 W., Meade Co.	8 ft. ash, sample 5 ft. above base; above sdy. silt	Snails below ash	17'''ff	1.499–1.501	0.06	.....	c	c	c	Crystalline inclusions; a few aggregates	Tr. qtz. sd.
36....	NE. Sec. 26, T. 32 S., R. 28 W., Meade Co.	18 ft. ash, pit sample 2 ft. above base; above clay & sd.; below silt	Snails below ash	17'''g	1.499–1.501	1.94	.....	c	c	vc	None	Tr. mica & qtz. sd.; a few brown insect parts
37....	NW. NW. Sec. 35, T. 33 S., R. 32 W., Seward Co.	7 ft. ash; above silt, sd., & gr.; below silt	Snails in ash	17'''f	1.499–1.501	2.07	2.31	c	c	c	None	None

TABLE 1—*Continued*

37....	NW. NW. Sec. 35, T. 33 S., R. 32 W., Seward Co.	7 ft. ash; above silt, sd., & gr.; below silt	Snails in ash	17‴f	1.499–1.501	2.07	2.31	c	c	c	None	Insect parts None

TABLE 1—*Continued*

No.	Location	Stratigraphic Position	Fauna	Color* (<62μ)	Refractive Index	Per Cent Fe_2O_3	Specific Gravity	Curved Junctures	Long Vesicles	Fibrous Shards	Alteration	Impurities
				Oklahoma								
38....	Sec. 8, T. 5 N., R. 28 E., Beaver Co.	30 ft. ash; above silty clay; below silt	Snails below ash	17⁗g	1.499–1.501	1.82	.....	?	c	?	None	?
39....	NW. Sec. 23, T. 23 N., R. 18 W., Woodward Co.	8 ft. ash, sample 2 ft. above base; above silt, sd., & gr.; below silt	Snails below ash	17‴ff	1.499–1.501	1.60	2.25	c	c	c	Crystalline inclusions; some opal	1% qtz. sd.
40....	E. ½ NW. Sec. 4, T. 18 N., R. 12 W., Blaine Co.	6 ft. ash; sample 2 ft. above base; above silt, sd., & gr.; below sd., silt	.....	17‴ff	1.499–1.501	1.77	.....	c	c	r	Shard outlines slightly anisotropic; surfaces dull	10% qtz. sd.
41....	NE. Sec. 24, T. 16 N., R. 16 W., Dewey Co.	4 ft. ash; above sdy. silt; below massive silt	.....	17‴f	1.499–1.501	3.03	2.30	vc	c	c	None	Tr. qtz. sd.
42....	SE. cor. NW. Sec. 15, T. 14 N., R. 16 W., Custer Co.	15 ft. ash, pit sample 4 ft. above base; above clay, silt, & sd.; below 8 ft. red, stratified silt & gr.	.....	17‴ff	1.499–1.501	1.34	2.30	c	r	r	None	None
44....	SE. cor. Sec. 28, T. 6 N., R. 18 W., Kiowa Co.	8 ft. ash; above silty clay; below 6 ft. massive silt & gr.	.....	17‴ff	1.499–1.501	1.64	2.22	c	c	c	A few crystalline inclusions	Tr. qtz. sd.
				Texas								
45....	NW. Sec. 14, Block B-1, Roberts Co.	8 ft. ash, sample 4 ft. above base; above silt, clay, & sd.; below massive silt	Snails below ash	16‴g	1.499–1.501	2.07	.....	vc	c	c	A few crystalline inclusions	None
46....	1 mi. N. of road, 8 mi. W. of Channing, Hartley Co.	>12 ft. ash capping butte, sample 3 ft. above base; above sds., silts, & clays	Snails below ash	16‴g	1.500?	2.64	2.26	c	vc	vc	Shard outlines anisotropic; surfaces dull	Tr. qtz. sd.
47....	SE. Sec. 90, Block 14, Collingsworth Co.	25 ft. ash, sample 4 ft. above base; above fn. sd. & silt	.....	17‴f	1.499–1.501	1.58	2.28	c	r	c	Slightly anisotropic outlines	Tr. qtz. sd.
48....	Edge caprock on Clarendon-Silverton Hwy., 13 mi. SW. of Antelope Flat, Briscoe Co.	12 ft. ash, sample 8 ft. above base; above 10 ft. sd. & silt, above Ogallala fm.; below massive silt & sd.	.....	17‴f	1.499–1.501	1.69	2.32	c	c	c	None	None
49....	11 mi. E. of Tulia, Swisher Co.	4 ft. ash, sample 1 ft. above base; above sd. & silt; below sd.	.....	17‴g	1.499–1.501	1.65	2.28	c	vc	c	Crystalline inclusions; a few aggregates	Tr. qtz. sd.
50....	2 mi. N. of McAdoo, Dickens Co.	10 ft. ash; above silty clay & silty sd.	.....	16‴ff	1.499–1.501	0.80	2.31	c	c	c	None	Tr. qtz. sd.
				Pliocene Ash								
A....	NW. SW. Sec. 23, T. 2 S., R. 22 W., Norton Co., Kan.	Pliocene [Ogallala fm.] (Swineford & Frye, 1946, p. 16)	.....	NGf	1.500–1.502	2.16–2.42	2.33–2.37	r	vr	vr	None	Tr. qtz. sd.
B....	N. line NW. NE. Sec. 30, T. 1 S., R. 19 W., Phillips Co., Kan.	Pliocene [Ogallala fm.]	.....	17‴ff	1.503–1.505	1.86	2.35	c	vr	vr	Crystalline inclusions	None
C.....	100 yds. N. of S. line SE. SE. Sec. 8, T. 14 S., R. 38 W., Wallace Co., Kan.	Pliocene [Ogallala fm.]	.....	16‴ff	1.503–1.505	2.17	2.35	c	vr	vr	None	None
D....	Hemphill Co., Tex. (Reed & Longnecker loc. 20)	Pliocene [Ogallala fm.] (Swineford & Frye, 1946, p. 17)	Hemphill fauna below ash	NGg	1.495–1.497	.....	.....	vr	vr	vr	Many crystalline inclusions; very dull surfaces; many aggregates	Qtz. sd.
				Miocene Ash								
E....	South-central Sioux Co., Neb., *Merychippus* Draw	Miocene [Sheep Creek fm. type locality]	.....	16⁗dd	1.505–1.507	7.22	2.32	vr	vr	vr	Very slight	Tr. qtz. sd.

Specific gravity determinations of thirty-two samples containing little detrital material or alteration products were made by pycnometer. The size grade 125–88 μ was used.

The results are reported in table 1. Five samples of older ash are included at the end of the table for comparative purposes. In comparing the results of chemical analyses and color determinations, more weight should be given to those samples which are fresh than to those in

TABLE 2

CHEMICAL ANALYSES OF SAMPLES OF VOLCANIC ASH*

No.†	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Ignition Loss‡	Undetermined Difference	Moisture‡
1	71.41	14.00	1.73	0.78	0.06	4.12	7.90	0.30
3	70.98	13.01	1.96	1.16	0.22	3.91	8.76	0.29
4	69.88	15.25	1.98	0.52	0.37	4.83	7.17	0.59
6	67.87	13.04§	1.68	0.66	5.58	4.12	7.05	0.41
7	71.29	13.29	1.81	0.82	0.21	4.06	8.52	0.30
8	70.44	13.07	1.84	0.87	0.26	4.61	8.91	0.31
9	75.02‖	11.17	1.63	3.72	0.40	4.40	3.67	0.95
10	70.46	13.48	2.08	1.31	0.34	3.94	8.19	.....
11	69.42	14.64	1.74	2.38	0.18	4.52	7.12	1.00
12	71.84	14.64	1.61	0.96	0.13	3.87	6.95	0.90
15	71.68	12.88	1.38	0.88	0.56	3.73	8.89	0.41
17	71.65	12.33	1.93	1.30	0.81	4.40	7.58	0.10
18¶	72.83	14.38	1.84	0.56	.....	5.53	4.86	.....
19	70.85	13.34	1.44	0.84	0.13	3.46	9.94	0.31
20	71.68	13.20	1.93	0.93	0.13	4.21	7.92	0.21
21¶	71.16	11.70	1.47	1.46	0.38	3.86	9.97	.....
22	71.99	13.51	1.18	1.05	0.13	3.90	8.24	0.32
23¶	72.77	13.87	1.82	0.87	.....	3.15	7.52	.....
24¶	73.30	14.46	1.54	1.00	0.21	4.60**	5.64††	.....
25	69.92	13.62	1.73	1.13	0.71	4.55	8.34	.....
29	71.88	14.12	1.91	0.95	0.33	4.22	6.39	.....
31	66.27	16.09	2.39	1.26	0.06	5.22	8.71	1.08
32	72.16	12.94	1.57	0.84	0.20	3.79	8.50	0.74
33	70.40	12.66	1.96	0.99	0.02	4.08	9.89	0.34
34¶	72.64	12.06	1.67	0.74	.....	4.24	8.65	.....
35	75.83	13.69	0.06	1.60	0.16	4.62	4.04	0.55
36	71.98	13.52	1.94	0.62	0.30	3.55	8.09	0.17
37¶	74.34	12.40	2.07	0.64	0.65	4.24	5.59††	.....
39	69.97	14.15	1.60	0.85	0.27	4.47	8.69	.....
41	71.31	17.31	3.03	1.01	.....	4.00	3.34	.....
42	72.53	14.14	1.34	1.19	0.37	4.20	6.23	.....
44	67.72	14.16	1.64	0.95	0.86	4.66	10.00‡‡	.....
45	71.74	14.22	2.07	1.11	0.43	4.16	6.27	0.34
46	72.16	16.96	2.64	0.51	.....	5.01	2.72	0.94
47	66.83	14.95	1.58	1.07	0.45	4.59	10.53§§	.....
48	70.80	12.40	1.69	0.56	0.32	4.16	10.07	0.09
49	69.24	12.66	1.65	1.36	1.96	4.69	8.44	0.28
50	70.70	12.35	0.80	1.17	2.83	3.75	8.40	0.15
B	69.77	12.88	1.86	1.41	1.02	5.26	7.80	.....
C	68.89	12.94	2.17	1.04	0.64	4.96	9.36	.....
E	59.32	24.93	7.22	2.52	0.95	5.08	−0.02	.....

* Analyses by Russell Runnels in the laboratories of the State Geological Survey of Kansas.
† Sample numbers refer to localities shown in fig. 1 which are listed in table 1.
‡ Samples dried to 140° C. and ignited to 1,000° C.
§ Includes 0.87 per cent TiO_2.
‖ Contains quartz sand.
¶ Analysis by Frances Schloesser (Swineford and Frye, 1946).
** Includes moisture.
†† Alkalies determined
‡‡ Includes K_2O, 5.07 per cent; Na_2O, 5.09 per cent.
§§ Includes K_2O, 5.00 per cent; Na_2O, 5.25 per cent.

which alteration has taken place or to those which have been contaminated by sand or silt.

Distinctive features of Pearlette ash.—In a previous comparison of Pearlette ash with various ash deposits of Pliocene age in Kansas, the following properties were found to be diagnostic of the Pearlette:

1. The color includes certain light shades of orange-yellow, which are not characteristic of fresh ash described from the Pliocene (Calvert mine).

2. The refractive index is consistently 1.499–1.501.

3. The shape of the shards is characteristically sharply curved, with thickened glass at the bubble junctures, which are commonly curved and branching at wide angles. Fibrous shards are present in all samples.

4. Many shards have groups or clusters of elongate vesicles which are seldom found in ash of Pliocene age.

5. The percentage of iron oxide is less than 2 as shown by eight of nine chemical analyses, with a range from 1.43 to 2.07 per cent; whereas in fifteen analyses of samples of Pliocene ash the Fe_2O_3 content ranges from 1.66 to 3.09, with only two samples below 2.00 per cent.

6. The specific gravity ranges from 2.21 to 2.32, whereas in the Pliocene ash it ranges from 2.33 to 2.37.

The color of most of the Pleistocene ash samples examined for this study is characteristic of the Pearlette, although in some it is modified by alteration of the glass. The refractive index corresponds to that of the type Pearlette in forty-six of the analyses; two samples were altered in such a way as to make determination doubtful.

The percentage of ferric oxide ranges from 0.06 (which is unexplained) to 3.03, six of the thirty-five samples analyzed showing an iron oxide content of more than 2.00 per cent. The high value for one of them (no. 34, 2.39 per cent) probably is due to the presence of red silt as an impurity. Sample 46, which has 2.64 per cent Fe_2O_3, may have gained in percentage of iron through alteration. The values for three other samples (nos. 10, 37, and 45, 2.08, 2.07, and 2.07 per cent, respectively) are only slightly higher than 2.00 per cent. No. 41, however, which shows a value of 3.03 per cent, is anomalous. It is thought to be Pearlette because its other parameters are the same as those of typical Pearlette.

The specific gravity ranges from 2.17 (altered sample 9) to 2.34, only one being higher than the range previously described for Pearlette ash. This sample, no. 12, also has fewer fibrous shards than typical Pearlette, but it is tentatively classed with that ash fall. The vesicles and the shapes of the shards of all samples (with the possible exception of no. 12) are of the Pearlette type.

The chemical analyses of Pleistocene ash in table 2 are very similar, except for magnesium oxide. The percentage of MgO is less than 1.00 except for three samples (6, 49, and 50), which consist of relatively fresh, unaltered ash; the large quantities of MgO are not explained.

In the present study, samples previously described from the Ogallala have been included, and samples from two more ash falls have been obtained in order to make further comparisons. They are described at the end of table 1.

A is Pliocene Ogallala ash from the Calvert mine, Norton County, Kansas. *B* and *C* represent another ash fall within the Pliocene Ogallala formation exposed in Phillips and Wallace counties, Kansas. *D* is another Ogallala ash from Hemphill County, Texas. *E* is ash of late Miocene age from the type locality of the Sheep Creek formation at *Merychippus* Draw in

Sioux County, Nebraska; it was submitted for our examination by C. Bertrand Schultz and T. M. Stout of the University of Nebraska State Museum. All differ in at least two respects from the Pearlette and from each other. Although the refractive index of *A* is close to that of the Pearlette, the color is a distinct gray, the iron content is high, and the shards are flatter than Pearlette shards and they lack elongate vesicles. *B* and *C* have the color and shape of Pearlette ash particles, except for the absence of fibrous shards, but have a higher refractive index and few elongate vesicles. *D*, a weathered sample, can be differentiated definitely from the Pearlette by its lower refractive index and its flat platy shards. *E* has almost nothing in common with the Pearlette; its refractive index is much higher, its color is a dark gray, most of its shards are characterized by two or more parallel, nearly straight bubble junctures, and vesicles are rare; its chemical analysis shows a low percentage of silica and a large amount of iron.

In using physical and optical properties of volcanic glass for correlation, it is necessary to assume that the characteristics of the glass from one ash fall (the Pearlette) will differ perceptibly from those of the glass in other ash falls in the same period and from the same source.

Such properties as the refractive index, specific gravity, and shape of shards depend not only upon the chemical composition of the magma but also upon such highly variable factors as the temperature of quenching, pressure, and gas content. Glass from acid magmas in particular may show much variation because of a wide range in temperature and other conditions at eruption (E. F. Osborn, oral communication). Therefore, it is unlikely that the glass shards from several different ash falls will have the same characteristics.

All other glasses studied in the central Great Plains which have a similar chemical composition to that of the Pearlette and are known to have been deposited from different ash falls can be distinguished from each other and from the Pearlette ash (table 1).

MOLLUSCAN FAUNA

Association of fauna with ash.—Assemblages of fossil mollusks occur in association with Pearlette volcanic ash at localities (fig. 1) distributed from Nebraska (loc. 6) and western Iowa (loc. 3) to northwestern Texas (loc. 46). Fossil mollusks were studied from eighteen localities where the snails were in immediate association with the ash and from a similar stratigraphic position at two localities (locs. 3 and 43) where ash did not occur. The molluscan fauna from localities 3 and 43 was later shown to possess the distinctive features of the Pearlette faunal assemblage.

The molluscan fauna of the Pearlette zone was first studied in southwestern and central Kansas (Frye, Leonard, and Hibbard, 1943) where fossils are abundant in blue-gray to tan silty clays, occurring from a few inches to 2 feet below the base of the volcanic ash lentils. In these areas, fossil remains of small mammals and other vertebrates occupy the same zone; they have been listed and described by Hibbard (1944), particularly from Meade, Russell, and Lincoln counties, Kansas. At other places (locs. 13 and 20) the snails are dispersed through as much as 5 feet of silt and sand below the ash; rarely, as in Seward County, Kansas (loc. 37), the mollusks are deposited with the ash itself. In the old Cudahy ash mine, near Orleans, Nebraska (loc. 9), the fossils were collected from near the top and just above the main bed of ash but below thin lenses of ash in the overlying silts of the Sappa

formation. At locality 25, in Dickinson County, Kansas, the molluscan fauna occurs both below and above the ash stratum in tan to gray silty clay with which the ash is interstratified.

Although the mollusks associated with the Pearlette volcanic ash consist of both aquatic and terrestrial forms, seemingly without exception they were deposited in depressions or shallow ponds; the aquatic forms were, no doubt, residents of the ponds themselves, whereas the terrestrial forms probably were washed in from near-by land areas. In some places (loc. 3) the ponds or lakes were so large that offshore deposits contain only aquatic species; the faunule of shoreline deposits consists predominantly of terrestrial gastropods. At most places the small size of ponds allowed a mixture of the forms from the two environments, although a few deposits contain a faunule comprised entirely of aquatic species or entirely of terrestrial forms.

Distinctive features of the fauna.—The occurrence and distribution of the sixty-five species and subspecies which have been distinguished in the Pearlette molluscan fauna are shown in figure 2, where species of the faunules are divided into five categories: (1) species ranging from lower Pliocene to Recent, (2) species ranging from Blancan to Recent, (3) species ranging from Blancan into the Pearlette faunal zone but not higher, (4) species restricted to the Pearlette zone, and (5) living species which make their first known appearance in Yarmouthian deposits. "Living species" is interpreted to mean forms which are living at some place within North America; many of these no longer live in the area under consideration.

No review of the literature concerned with Pleistocene fossil mollusks is given here, inasmuch as the Pearlette fauna will be reported upon in detail in a study now in preparation. All specimens which comprise the basis for this report and the faunal paper to follow are catalogued in the molluscan collections of the University of Kansas Museum of Natural History.

It is obvious that assemblages of any fossil organisms are useful for purposes of stratigraphic correlation only if an assemblage, associated with some specific stratigraphic unit, possesses at the same time features which distinguish it from assemblages of similar organisms that are known to occur in deposits of different stratigraphic placement. Furthermore, the usefulness of distinctive elements of an assemblage is limited by their regional distribution, unless it can be shown that certain species of one region are comparable in evolutionary development to those in another region at the same stratigraphic level or unless it can be shown that the changes in elemental composition of an assemblage, from one region to another, are due entirely to regional variation in climate or to other environmental factors.

In order to discriminate between distinctive and less meaningful elements of the Pearlette molluscan fauna and to assist in evaluating the various components of this fauna, the species have been grouped under the five categories previously mentioned. This grouping is intended to emphasize two features of the fauna: (1) the vertical range of species and (2) the regional distribution of species, especially with regard to occurrence in the glaciated portion of the region under study and the occurrence in the nonglaciated Plains portion of the region.

The four species (fig. 2, nos. 1–4) which range from the early Pliocene Laverne formation (Leonard and Franzen, 1944) to the Recent are of little significance for present purposes, except that nos. 2, 3, and 4 are distributed across

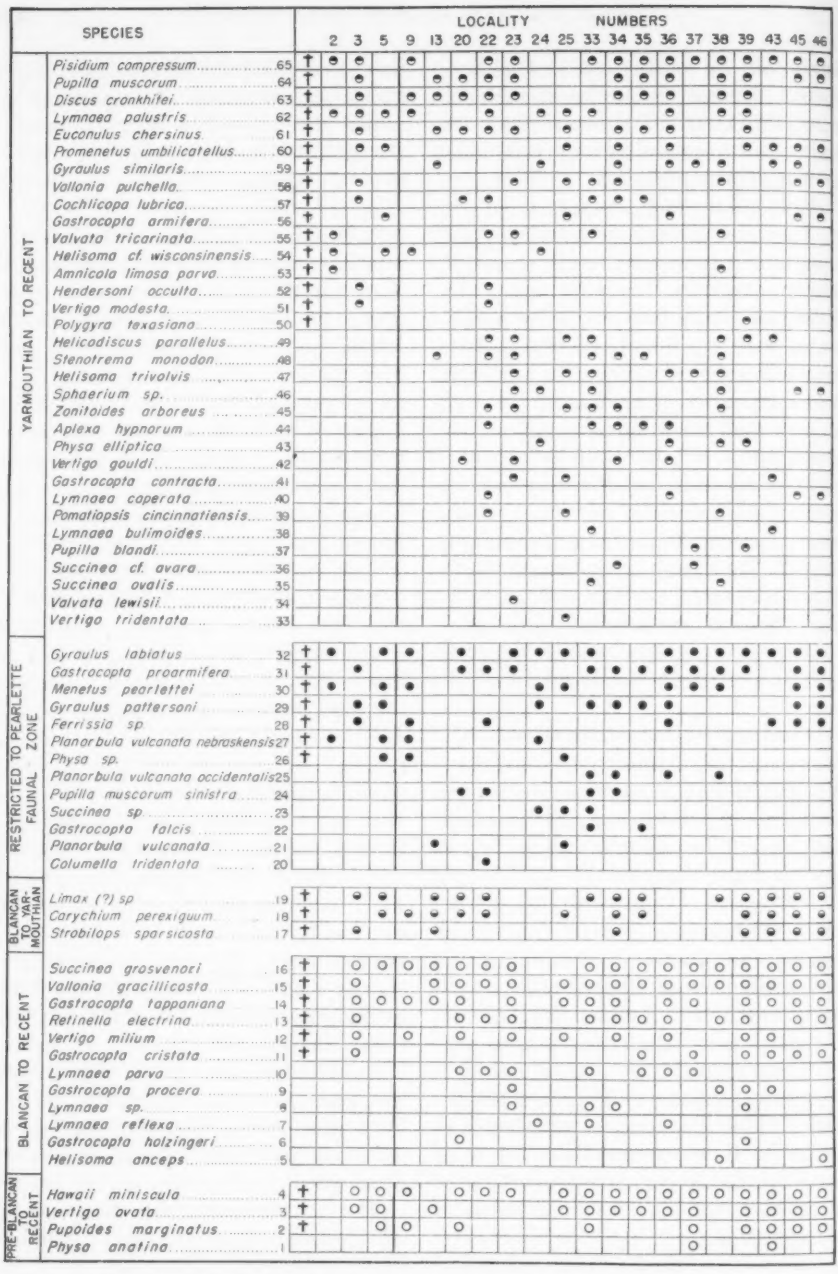


FIG. 2.—Chart showing distribution and occurrence of the 65 species comprising the Pearlette faunal assemblage. The species are grouped according to their vertical range. Species marked † are those which occur on either side of the glacial border.

the glacial border and serve to indicate widespread uniformity of ecological conditions at the time the beds containing them were being deposited. The twelve species in the next category (fig. 2, nos. 5–16) are of similar significance; the local occurrence of members of both groups does, however, contribute to a knowledge of environmental conditions at a specific place.

Three species (fig. 2, nos. 17–19) are not known to occur in deposits younger than those associated with the Pearlette ash. However, since they are known from Blancan deposits, they are useful as indices only when found directly associated with the Pearlette ash or when by other means it can be shown that the deposits are not Blancan in age. The fossilized internal shells of a large slug (no. 19), belonging to the molluscan family Limacidae, are of particular interest, since there are no living representatives of this family in the United States which possess internal shells of the type found as fossils in the Pearlette fauna. These shells have not been found in deposits of undoubted Pliocene age, but they are common in Blancan deposits.

Thirteen species or subspecies (fig. 2, nos. 20–32) are, as far as known, restricted in their occurrence to the Pearlette zone. This group is of great significance for purposes of regional correlation of the deposits containing them, since their vertical distribution is limited, and their value is further enhanced by the fact that a majority of this group (nos. 26–32) occurs both in localities within the glaciated portion of the region under study and in localities in the Plains region.

The largest group of species (fig. 2, nos. 33–65) is composed of those which range upward to Recent deposits (Leonard and Frye, 1943; Hibbard, Frye, and Leonard, 1944) but which make their first known appearance in the Pearlette faunal zone. Among these fossils are representatives of seven genera (*Cochlicopa*, *Discus*, *Pupilla*, *Stenotrema*, *Vallonia*, and *Valvata*) which are not known to occur in older faunal zones within the area under study. Sixteen of the species in this group (fig. 2, nos. 50–65) have wide distribution and occur in localities on either side of the glacial border. Since these species range upward into younger deposits, they are useful for stratigraphic correlation only when definitely associated with the ash or other distinctive elements of the fauna.

In all, thirty-five species, comprising more than half the total assemblage associated with the Pearlette volcanic ash, are widely distributed and are found both within glaciated territory and outside the glacial border. This wide distribution of many species, together with the fact that 20 per cent of the total number of species is restricted to the Pearlette faunal zone, gives the Pearlette assemblage distinctive qualities that serve to prove the essential contemporaneity of the sediments deposited in the zone. This confirms similar conclusions based on petrographic and stratigraphic data.

The distinctive features of the Pearlette faunal assemblage are summarized in figure 2.

PALEOPHYSIGRAPHIC ASPECTS

The stratigraphic succession of stream-deposited sediments is of small value for regional correlation of Pleistocene units beyond the margins of the till sheets. The repeated episodes of continental glaciation gave rise to repeated successions of fluviatile sediments that resemble one another in many respects. In Nebraska these successions of sediments have been referred to as cycles (Schultz

and Stout, 1945, 1948; Condra, Reed, and Gordon, 1947; Lueninghoener, 1947) and treated as stratigraphic units, although each cycle contains named formations. In the lower Mississippi Valley, Fisk (1939, 1944) has described a comparable sequence of sediments, to which he applied formation names, one such formational unit being distinguished under each of the major Pleistocene terrace surfaces.

In the Great Plains major modifications of drainage during Pleistocene time seem to have prevented the development of orderly downward terrace steps such as occur in the lower Mississippi Valley. Thus, in this region, stratigraphic succession is not a usable tool for correlation over wide areas unless some special lithologic element, such as a volcanic ash deposit or a buried soil, is present in the cyclic sequence of sediments. Furthermore, paleophysiography is less usable in the Plains than in some other regions because locally younger sediments occur stratigraphically above older, whereas at other places within the Great Plains younger sediments occur on successively lower terraces, and at still other localities only part of the cyclic episodes are recorded. Paleophysiographic techniques are usable in local areas or in areas that possess a unified drainage history.

Perhaps the most important contribution paleophysiography can make toward the integration of Great Plains Pleistocene stratigraphy with the glacial section is the determination of the time relationship between fluvial and glacial cycles. Quite clearly, each cyclic episode of valley cut and fill is controlled directly by the advance and retreat of a continental ice sheet and by the associated climatic change, melt waters, fluctuations of sea-level, or isostatic depression and marginal superelevation of the earth's crust.

If, in the area peripheral to the ice, valley cutting was accomplished throughout interglacial times and filling throughout glacial times, the sediments serve as record only of the glacial episodes. If, on the other hand, valley cutting was accomplished during the glacial episodes, the sediments are a record of interglacial time. Still another possibility is that cutting of valleys took place during the advance and maximum stand of continental ice sheets (Ireland, 1946), alluviation of the valleys during the retreating phase of each glaciation, and that interglacial time was an interval of approximate equilibrium when soil making was the most important process. Several lines of evidence, including the nature of the fluvial sediments, relation of old soils to the several cycles of sedimentation, and physiographic history, suggest that the last of these three possibilities obtained in the region under investigation.

STRATIGRAPHIC CONCLUSIONS

The establishment of the Pearlette volcanic ash zone as a datum of Yarmouthian age furnishes us with means for correlating the Great Plains Pleistocene section with the stratigraphic succession of the glaciated areas and for interrelation of events in the late Cenozoic history of the Plains with glacial chronology. Furthermore, it makes possible a major step toward unification of stratigraphic nomenclature for the cycle of sedimentation that contains the volcanic ash lentils. A diversity of stratigraphic names has been used for Pleistocene deposits in different parts of the Plains, and only in Nebraska has a terminology of state-wide scope been proposed. By utilizing terms adopted in Nebraska as member-names within the Sanborn formation (Frye and Fent, 1947), the nomenclature of the late Pleistocene deposits has been unified

throughout much of Kansas. It is here proposed to effect the same type of unification for the remaining post-Kansas till deposits of this region. Available data are not sufficient to allow similar treatment of the pre-Kansan Pleistocene deposits in the Great Plains region. Correlations and proposed nomenclatures are shown in figure 3.

PROBLEMS OF THE BLANCAN

It is not the purpose of this paper to discuss the many problems that have arisen concerning placement of the Pliocene-Pleistocene boundary line. It is needful, however, to give attention to the cycle of fluvial sedimentation preceding the Kansan cycle in order to place deposition of the Pearlette zone in its proper perspective in Pleistocene history.

In the Nebraska area peripheral to the ice front, the cycle of coarse to fine sediments occurring stratigraphically below the "post-Kansas-till-sediments" has been classed as Holdrege and Fullerton formations (Lugn, 1935). These units have been correlated (Condra, Reed, and Gordon, 1947) with the Broadwater formation (Schultz and Stout, 1945), which occupies a high terrace position in western Nebraska and which has yielded an abundant fauna correlated with the Blancan (Wood, *et al.*, 1941) fauna of northwestern Texas. In Texas, where the type section of the Blanco and correlative deposits have been restudied recently (Evans and Meade, 1945; Meade, 1945), the deposits of Blancan age in Rita Blanca Canyon, west of Channing (loc. 46), occur below Pleistocene sediments that contain Pearlette ash and an associated snail fauna.

In central Kansas the pre-Kansan cycle of sediments occupies the bottom of a deep filled valley in Rice County where numerous test holes have revealed its presence below the strata of the Kansan cycle (including the Pearlette ash) and younger Pleistocene deposits (personal communication from O. S. Fent). This filled and abandoned valley was cut about 200 feet in bedrock after the deposition of the Pliocene Ogallala formation and before the deposition of the Blancan sediments (Frye and Fent, 1947, p. 46).

In southwestern Kansas the Rexroad formation occurs unconformably below the Meade formation, which contains the Pearlette ash and associated vertebrate and molluscan faunas. In this region, however, the relationships of the several units have been obscured partly by faulting and solution-subsidence. Furthermore, the inclusion (McLaughlin, 1946; Byrne and McLaughlin, 1948) in the Rexroad formation of beds that have yielded fossil vertebrates indicating an age older than type Rexroad fauna and the exclusion of other beds formerly mapped with Rexroad suggest that more than one pre-Kansan cycle has been included in the formation.

Data from these areas demonstrate the existence of a pre-Kansan cycle of alluvial sedimentation, associated with Nebraskan glaciation, that has been assigned to the Blancan provincial age (Wood, *et al.*, 1941; Elias, *et al.*, 1945) (although it may not represent all of Blancan time); this pre-Kansan body of sediments is separated from the Ogallala formation of Pliocene age by an important regional unconformity.

The Blancan faunas recently have been assigned by some workers (Schultz and Stout, 1941, 1945, 1948; McGrew, 1944; Evans and Meade, 1945) to early Pleistocene time and by others to late Pliocene time (Hibbard, 1937, 1941*a*, 1941*b*; G. G. Simpson, 1947; Frye and Hibbard, 1941*b*). Simpson (1947, p. 623) has correlated the Blancan with the Villafranchian and Astian of Europe, which are generally classed as Pliocene; accord-

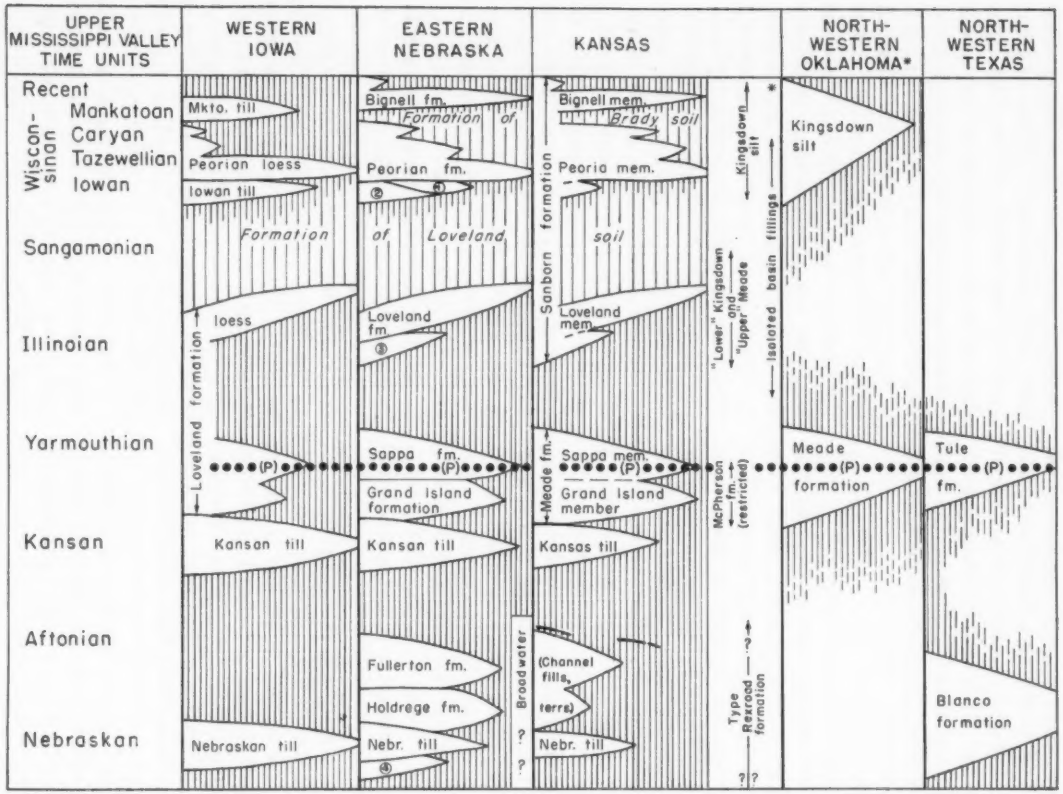


FIG. 3.—Chart showing classification and correlation of various stratigraphic units from the Missouri Valley area into the central Great Plains. The stratigraphic position of the Pearlette volcanic ash is shown by large dots.

ingly, he has interpreted the Blancan vertebrates as late Pliocene in age, but he did not correlate the Blancan deposits with the glacial sequence of north-central United States. Schultz and Stout (1948) suggest that the Blancan correlates with the Villafranchian of Europe and that the Plaisancian-Astian fauna may be represented in America by the fossil mammals of the Ash Hollow and Kimball (including Sidney) formations of Nebraska classification. The evidence presented here shows that the cycle of sedimentation represented by Holdrege-Fullerton (Broadwater) in Nebraska, the Blanco formation in Texas, the earliest channel fills of central Kansas, and the upper part, at least, of the Rexroad formation in southwestern Kansas are related to Nebraskan glaciation; and in terms of glacial chronology they should be placed in late Nebraskan and early Aftonian time. This correlation does not preclude their assignment to late Pliocene time if the beginning of Pleistocene time is interpreted to belong after the withdrawal of the first major ice sheet, following the view of some European workers (Gromov, 1945).

As the present study is concerned primarily with the Kansan cycle of sediments, which contains the Pearlette volcanic ash zone, no attempt is made here to modify the existing terminology of the pre-Kansan sediments. Figure 3 shows the names now in common use in several areas and their correlation with the generally accepted time scale developed in the upper Mississippi Valley.

FIG. 3.—Chart showing classification and correlation of various stratigraphic units from the Missouri Valley area into the central Great Plains. The stratigraphic position of the Pearlette volcanic ash is shown by large dots.

CLASSIFICATION IN KANSAS

It is here proposed to restrict the Meade formation (Frye and Hibbard, 1941*b*) to sediments at its type section, NW. ¼, Sec. 21, T. 33 S., R. 28 W., Meade County, Kansas, and equivalent deposits elsewhere, which signifies that this term should be used throughout Kansas to include the sediments of the Kansan cycle of fluvial sedimentation. Also, two members of the Meade formation are recognized, namely, the Grand Island member, below, and the Sappa member, above; the latter includes the Pearlette volcanic ash lentil. Frye and Fent (1947) have revised the classification of late Pleistocene deposits underlying extensive areas in the northern half and the south-central part of Kansas. The unification of terminology produced by this classification is indicated in the correlation chart, figure 3.

Meade formation.—The sediments of the Kansan cycle of alluviation constitute the best developed and most widely occurring Pleistocene stratigraphic unit, exclusive of the loesses, in the central Great Plains. Although the Blancan deposits have perhaps attracted more general notice among geologists because of their abundant fossil vertebrate fauna and controversial age, they occur only at scattered localities. The post-Meade cycles are less well developed and in some drainage basins hardly recognizable.

It was after the deposition of the Meade formation and correlative sediments that the most extensive modifications of the early Pleistocene drainage pattern occurred, and, as a result, these deposits are preserved in segments of former major valleys that no longer contain through-flowing streams. This early Pleistocene drainage, at least south of Nebraska, seemingly did not cross the Flint Hills area to join the Missouri-Mississippi system, as it now does, but flowed toward the south or southeast across Kansas and northern Oklahoma. Drainage from the western margin of the continental ice sheets and from the Rocky Mountain region converged west

of the Flint Hills area, and only after the retreat of the Kansan ice sheet was this Great Plains drainage diverted to the east. Notable among these abandoned valley segments are those of McPherson County and Lincoln and Ellsworth counties, Kansas. In McPherson County an abandoned valley (Lohman and Frye, 1940) extends from the present valley of the Smoky Hill River to the Arkansas River. The alluvial fill clearly displays sand and gravel (Grand Island member of the Meade formation) overlain conformably by stratified sand and silt which includes the Pearlette volcanic ash (Sappa member of the Meade formation), which is overlain in turn by Loveland silt of the Sanborn formation. The well-known fossil vertebrate fauna referred to as the "Equus beds" or McPherson fauna (Frye and Hibbard, 1941*a*) was collected from the Grand Island sand and gravel below the Pearlette volcanic ash. The abandoned-valley segment in Lincoln and Ellsworth counties, Kansas, has been called the Wilson Valley (Frye, Leonard, and Hibbard, 1943; Frye, 1945*b*) and extends across the present divide between the Saline Valley and the Smoky Hill Valley. Also, the succession of sediments in this area closely resembles that in the McPherson Valley of central Kansas; at Fullerton, Nebraska; near Little Sioux, Iowa; and at many other localities where this unit has been studied in exposures and in drill cuttings.

At the type locality of the Meade formation, sedimentation was in part controlled by solution-subsidence and related faulting, and the Sappa member, which contains the Pearlette volcanic ash of the type area (pl. 2, *A*), is unusually thick. It here contains beds of silty clay indicative of slack-water conditions. The Grand Island sand and gravel at the base of the type section nevertheless reflects a Rocky Mountain source and was probably deposited by a through-flowing stream trending toward the south-southeast.

At several localities in the High Plains, typically in Gove County, Kansas (loc. 20; pl. 1, *D*), and at several places in northwestern Texas (where this unit has been called the Tule formation) the Grand Island member consists largely or entirely of locally derived materials and presumably is a deposit of tributary streams that did not tap a glacial or mountain sedimentary source. This also is true at localities 25 and 26, within and on the east flank of the Flint Hills. Here this cycle is represented by deposits derived from the Permian bedrock of the region and contains the Pearlette volcanic ash in relatively coarse materials. The volcanic ash, which was not affected by drainage divides, and the snail fauna of the Sappa member, are nonetheless diagnostic.

The physiographic position of the Kansan cycle of sediments (Meade formation) varies in different areas owing to the differences in drainage history. In parts of eastern Nebraska (for example, near Fullerton) and western Iowa along the Missouri River bluffs, various Pleistocene sediments occur in stratigraphic sequence, the several units of cyclic sediments being set apart by unconformities. A similar stratigraphic succession is widely present in southwestern and parts of central Kansas, where the Pleistocene deposits fill deep valleys cut below the Ogallala surface or fill solution-subsidence or down-faulted areas.

Throughout much of the Kansas River Basin a physiographic sequence is distinguished, consisting of successively lower terraces, and this is comparable in some respects to the terrace succession of the lower Mississippi Valley described by Fisk (1939, 1944). The Meade formation

is particularly prominent along Smoky Hill River underlying the surface of a high terrace in Russell and Ellsworth counties, Kansas. In the panhandle region of Texas, deposits correlative with the Meade formation (Tule formation of Texas classification) occur stratigraphically above the Blanco formation or, where the Blanco is absent, above the Ogallala formation, and their upper surface is approximately accordant with the High Plains surface. In some places (loc. 48) the Tule formation is exposed at the crest of the High Plains escarpment, high above the lowland developed by the tributaries of the Red River system.

Sanborn formation.—In 1947 Frye and Fent reviewed usage of the Sanborn formation and expanded its geographic application to cover all of northern and central Kansas. It represents the time span of the Kingsdown silt of southwestern Kansas and correlative deposits of the panhandle regions of Oklahoma and Texas. The Sanborn formation includes beds classed by the Nebraska Geological Survey as Crete, Loveland, Todd Valley, Peorian, and Bignell formations and classed by the Iowa Geological Survey as Loveland loess and Peorian loess. In Kansas three members—Loveland silt, Peoria silt, and Bignell silt—which are separated by the Loveland and Brady (Schultz and Stout, 1948) soils, have been defined within the Sanborn formation. These members are stratigraphic equivalents to the comparably named units, which are classed as formations in Nebraska.

In Nebraska the deposits here included within the Sanborn formation are considered to represent several cycles of sedimentation that reflect the advance and retreat of Illinoian and the several Wisconsinan ice sheets (Schultz and Stout, 1945, 1948; Condra, Reed, and Gordon, 1947). Owing to the fact that these late Pleistocene ice invasions did not approach the central Great Plains region so closely as did the Kansan and Nebraskan, the cyclic repetition of valley cut and fill is much less well developed than is the case with the Nebraskan and Kansan cycles. Furthermore, the most widespread deposits assignable to the Sanborn are the loess sheets that mantle vast areas of the uplands and are, in many places, separated only by fossil soils. Therefore, the present classification that groups together the several late Pleistocene cycles into one formational unit seems most consistent with usable field practices in the central Great Plains.

ACKNOWLEDGMENTS.—The manuscript for this paper was improved by the advice and criticisms of Raymond C. Moore, state geologist of Kansas. We express our thanks to the following persons who read and criticized the manuscript: H. G. Hershey, state geologist of Iowa, and A. C. Trowbridge of the University of Iowa; E. P. Rothrock, state geologist of South Dakota; G. E. Condra, state geologist, and E. C. Reed, associate state geologist of Nebraska; C. Bertrand Schultz, director, and T. M. Stout of the University of Nebraska State Museum; R. H. Dott, director, and S. L. Schoff of the Oklahoma Geological Survey; J. W. Stovall of the University of Oklahoma; J. T. Lonsdale, director, and G. L. Evans and G. E. Meade of the Texas Bureau of Economic Geology. Accompanying us on the May, 1947, field conference were, among those mentioned above, Trowbridge, Hershey, Stout, Schultz, and Reed; and, in addition, S. E. Harris, C. S. Gwynne, A. L. Lugn, W. D. Frankforter, and G. C. Lueninghoener. In August, 1947, Schultz, Stout, Lueninghoener, and Frankforter kindly guided us to the outcrops near Orleans, Nebraska. Richard F. Flint generously furnished us with data concerning the stratigraphy of the glacial deposits in the vicinity of locality 1 in southeastern South Dakota. During the early stages of field work on stratigraphy of the Pearlette volcanic ash in southwestern Kansas invaluable aid was given us by C. W. Hibbard, formerly curator of vertebrate paleontology at the University of Kansas Museum of Natural History.

REFERENCES CITED

BYRNE, F. E., and MCLAUGHLIN, T. G. (1948) Geology and ground-water resources of Seward County, Kansas: Kansas Geol. Survey Bull. 69.

CONDRA, G. E.; REED, E. C ; and GORDON, E. D. (1947) Correlation of the Pleistocene deposits of Nebraska: Nebraska Geol. Survey Bull. 15, pp. 1–73.

CRAGIN, F. W. (1896) Preliminary notice of three late Neocene terranes: Colorado Coll. Studies, vol. 6, pp. 53–54.

ELIAS, M. K., *et al.* (1945) Blancan as a time term in the central Great Plains: Science, vol. 101, no. 2620, pp. 270–271.

EVANS, G. L., and MEADE, G. E. (1945) Quaternary of the Texas High Plains: Univ. Texas Pub. 4401, pp. 485–507.

FISK, H. N. (1939) Depositional terrace slopes in Louisiana: Jour. Geomorphology, vol. 2, pp. 181–200.

——— (1944) Geological investigation of the alluvial valley of the lower Mississippi River: War Dept., Corps of Engineers, Mississippi River Comm., Vicksburg, Mississippi.

FLINT, R. F. (1947) Glaciation of South Dakota (preliminary discussion) (abstr.): Geol. Soc. America Bull. 58, pp. 1179–1180.

FRYE, J. C. (1942) Geology and ground-water resources of Meade County, Kansas: Kansas Geol. Survey Bull. 45.

——— (1945*a*) Problems of Pleistocene stratigraphy in central and western Kansas: Jour. Geology, vol. 53, pp. 75–93.

——— (1945*b*) Valley erosion since Pliocene "algal limestone" deposition in central Kansas: Kansas Geol. Survey Bull. 60, pt. 3, pp. 85–100.

——— (1946) Review of studies of Pleistocene deposits in Kansas: Am. Jour. Sci., vol. 244, pp. 403–416.

——— and FENT, O. S. (1947) The late Pleistocene loesses of central Kansas: Kansas Geol. Survey Bull. 70, pt. 3, pp. 29–52.

——— and HIBBARD, C. W. (1941*a*) Stratigraphy and paleontology of a new Middle and Upper Pliocene formation of south-central Kansas: Jour. Geology, vol. 49, pp. 261–278.

——— — ——— (1941*b*) Pliocene and Pleistocene stratigraphy and paleontology of the Meade Basin, southwestern Kansas: Kansas Geol. Survey Bull. 38, pp. 389–424.

———; LEONARD, A. B.; and HIBBARD, C. W. (1943) Westward extension of the Kansas "Equus beds"; Jour. Geology, vol. 51, pp. 33–47.

GROMOV, V. (1945) Twenty-five years of study of the Quaternary in the U.S.S.R.: Am. Jour. Sci., vol. 243, pp. 492–516.

HIBBARD, C. W. (1937) An Upper Pliocene fauna from Meade County, Kansas: Kansas Acad. Sci. Trans., vol. 40, pp. 239–265.

——— (1941*a*) Paleoecology and correlation of the Rexroad fauna from the Upper Pliocene of southwestern Kansas, as indicated by the mammals: Kansas Univ. Sci. Bull. 27, pp. 79–104.

——— (1941*b*) Mammals of the Rexroad fauna from the Upper Pliocene of southwestern Kansas: Kansas Acad. Sci. Trans., vol. 44, pp. 265–313.

——— (1944) Stratigraphy and vertebrate paleontology of Pleistocene deposits of southwestern Kansas: Geol. Soc. America Bull. 55, pp. 707–754.

———; FRYE, J. C.; and LEONARD, A. B. (1944) Reconnaissance of Pleistocene deposits in north-central Kansas: Kansas Geol. Survey Bull. 52, pp. 1–28.

IRELAND, H. A. (1946) Cause and age of Pleistocene entrenchment in the Ohio and Lake Erie basins (abstr.): Geol. Soc. America Bull. 57, pp. 1206–1207.

KAY, G. F. (1924) Recent studies of the Pleistocene in western Iowa (abstr.): Geol. Soc. America Bull. 35, pp. 71–73.

——— and APFEL, E. T. (1928) The pre-Illinoian Pleistocene geology of Iowa: Iowa Geol. Survey, vol. 34, pp. 1–304.

——— and GRAHAM, J. B. (1943) The Illinoian and post-Illinoian Pleistocene geology of Iowa: Iowa Geol. Survey, vol. 38, pp. 11–262.

LANDES, K. K. (1928) Volcanic ash resources of Kansas: Kansas Geol. Survey Bull. 14.

LEONARD, A. B., and FRANZEN, D. S. (1944) Mollusca of the Laverne formation (Lower Pliocene) of Beaver County, Oklahoma: Kansas Univ. Sci. Bull. 30, pp. 15–39.

——— and FRYE, J. C. (1943) Additional studies of the Sanborn formation, Pleistocene, in northwestern Kansas: Am. Jour. Sci., vol. 241, pp. 453–462.

LOHMAN, S. W., and FRYE, J. C. (1940) Geology and ground-water resources of the "Equus beds" area in south-central Kansas: Econ. Geology, vol. 35, pp. 839–866.

LUENINGHOENER, G. C. (1947) The post-Kansan geologic history of the Lower Platte Valley area: Univ. Nebraska Studies, new ser., no. 2.

LUGN, A. L. (1935) The Pleistocene geology of Nebraska: Nebraska Geol. Survey Bull. 10, pp. 1–223.

MCGREW, P. O. (1944) An early Pleistocene (Blancan) fauna from Nebraska: Field Mus. Nat. History Pub., Geol. ser., vol. 9, no. 2, pp. 33–66.

MCLAUGHLIN, T. G. (1946) Geology and ground-water resources of Grant, Haskell, and Stevens counties, Kansas: Kansas Geol. Survey Bull. 61.

MEADE, G. E. (1945) The Blanco fauna: Univ. Texas Pub. 4401, pp. 509–556.

RIDGWAY, ROBERT (1912) Color standards and color nomenclature, Washington, D.C.

SCHULTZ, C. B., and STOUT, T. M. (1941) Guide for a field conference on the Tertiary and Pleistocene of Nebraska (in collaboration with A. L. Lugn, M. K. Elias, F. W. Johnson, and

M. F. Skinner), first field conference of the Society of Vertebrate Paleontology, 1941; Univ. Nebraska State Mus., Special Pub., pp. 1–15.

——— — ——— (1945) Pleistocene loess deposits of Nebraska: Am. Jour. Sci., vol. 243, pp. 231–244.

——— — ——— (1948) Pleistocene mammals and terraces in the Great Plains: Geol. Soc. America Bull. (in press).

SIDWELL, RAYMOND, and BRONAUGH, R. L. (1946) Volcanic sediments in north Texas: Jour. Sedimentary Petrology, vol. 16, pp. 15–18.

SIMPSON, G. G. (1947) Holarctic mammalian faunas and continental relationships during the Cenozoic: Geol. Soc. America Bull. 58, pp. 613–688.

SIMPSON, H. E. (1947) Pleistocene geology of the Yankton area, South Dakota and Nebraska (abstr.): Geol. Soc. America Bull. 58, pp. 1228–1229.

SMITH, G. D., and RIECKEN, F. F. (1947) The Iowan drift border of northwestern Iowa: Am. Jour. Sci., vol. 245, pp. 706–713.

SWINEFORD, ADA, and FRYE, J. C. (1946) Petrographic comparison of Pliocene and Pleistocene volcanic ash from western Kansas: Kansas Geol. Survey Bull. 64, pt. 1, pp. 1–32.

TODD, J. E. (1892) Volcanic dust from Omaha, Nebraska: Am. Geologist, vol. 10, pp. 295–296.

——— (1895) Volcanic ash bed near Omaha: *ibid.*, vol. 15, p. 130.

——— (1899) The moraines of southeastern South Dakota and their attendant deposits: U.S. Geol. Survey Bull. 158.

WARREN, C. R. (1947) Iowan till at Chamberlain, South Dakota (abstr.): Geol. Soc. America Bull. 58, p. 1237.

WOOD, H. E., *et al.* (1941) Nomenclature and correlation of the North American continental Tertiary: Geol. Soc. America Bull. 52, pp. 1–48.

BLACK HILLS TERRACE GRAVELS: A STUDY IN SEDIMENT TRANSPORT[1]

WILLIAM J. PLUMLEY
University of Chicago

ABSTRACT

Terraces were mapped along three streams which flow eastward from the Black Hills of South Dakota. Five erosional surfaces were found which represent major pauses in the downcutting activity of the regional drainage. The presence of knickpoints in the present-day stream profiles offers proof that the more recent terraces of this region are the result of factors controlling downcutting downstream in the Cheyenne and Missouri rivers. These factors are best explained on the basis of Pleistocene glaciation in eastern South Dakota.

Twenty-three channel samples were taken from the terraces of Bear Butte, Rapid, and Battle creeks. In addition, sand samples 1–2 mm. in size were collected from the headwaters of Battle Creek near Harney Peak to the lower end of the Cheyenne River where it flows into the Missouri River, a distance of about 200 miles. The samples were analyzed for size, shape, roundness, and lithology. Systematic changes as a function of distance were observed for mean size, skewness, lithology, shape, and roundness. The rate of rounding was found to be directly proportional not only to the difference between the roundness at some point and a limiting roundness but also to some power of the distance transported.

An attempt is made to express quantitatively the effects of stream transport on roundness and lithology in respect to "indices of maturity."

INTRODUCTION

The field of sedimentology has rapidly advanced with the advent of modern methods of sediment analysis. Emphasis has shifted from the purely descriptive aspects of the science to an analytic approach. With this change in viewpoint the fundamental attributes of sedimentary particles have received much attention. These attributes, such as size, shape, and roundness, to name but a few, have been extensively studied by mathematical and statistical methods. The result of such methods has been to furnish a large amount of data which again tend to be merely descriptive. Far more important than the fact that a gravel deposit has a specific type of size-frequency distribution is the statement of what genetic factors were involved in producing that distribution.

The statement of these genetic factors involves a study of environments of deposition and, in addition, knowledge of the previous history of the material being deposited. This knowledge has too often been derived from theoretical reasoning rather than from experimental fact. The present research has been conducted with the purpose of adding to this knowledge by means of field observations.

The fundamental attributes of sediments are affected to a greater or less degree by transportation in streams. The present work is concerned with the effects of transportation on the attributes of size, shape, roundness, and lithology.

The work is presented in two parts. The first considers the physiographic expression and development of certain stream terraces within and east of the Black Hills of South Dakota. The second part is concerned with the sampling and analysis of material from these terraces.

PHYSIOGRAPHY

GEOLOGIC SETTING

The area of study includes the eastern border of the Black Hills of South Dakota and adjacent portions of the Missouri Plateau section of the Great Plains (fig. 1).

[1] Manuscript received July 30, 1948.

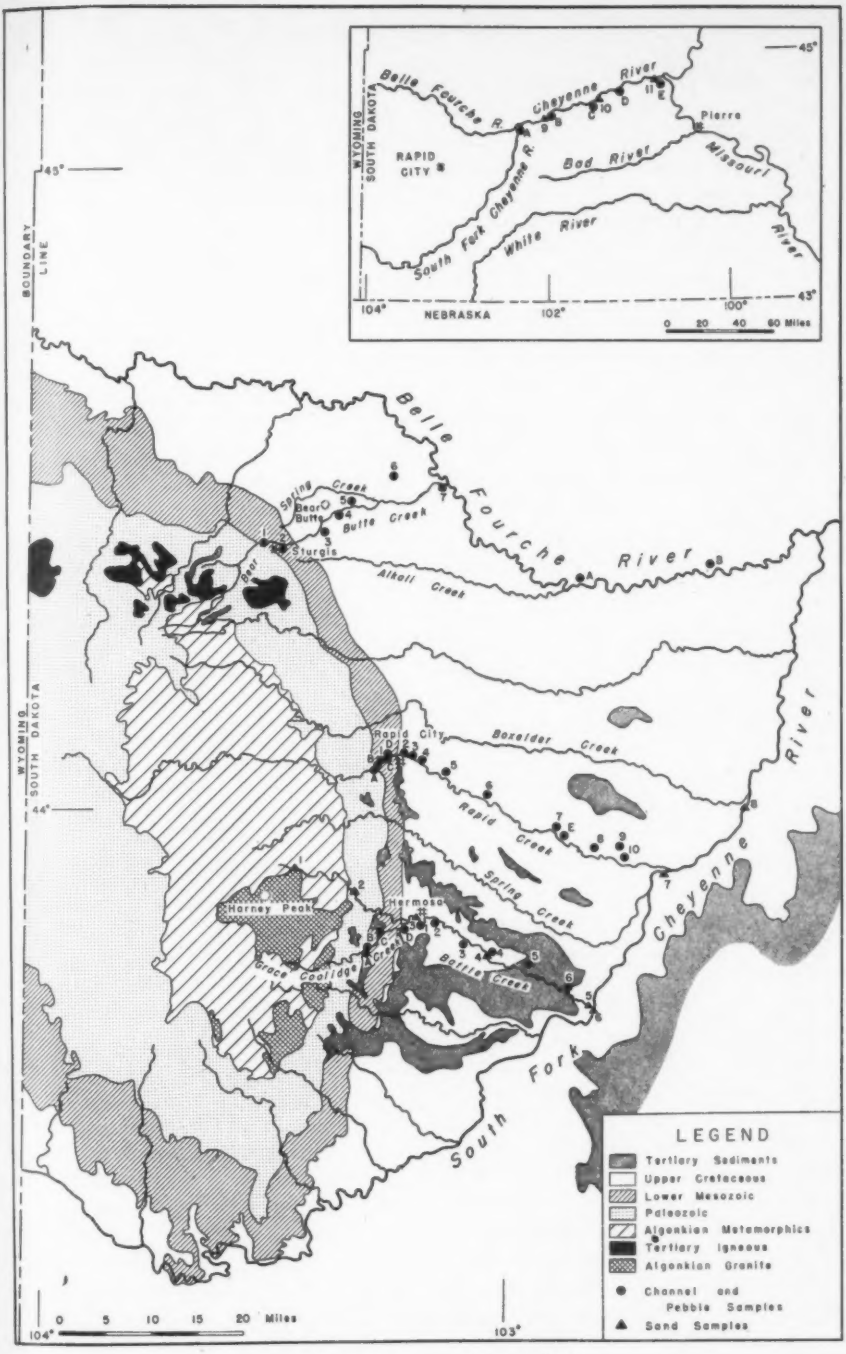


FIG. 1.—Index map of area studied

The Black Hills are an ovate mountainous area of moderate relief underlain by pre-Cambrian crystalline rocks and flanked by tilted sedimentary formations ranging in age from Cambrian to Cretaceous. Tertiary intrusives are found in the northern Hills, and flat-lying Tertiary sediments overlap Mesozoic formations on the plains to the east.

The Black Hills lie entirely within the drainage basin of the Cheyenne River and are encircled by two major tributaries, the Belle Fourche River on the north and the Cheyenne South Fork on the south. From the junction of these tributaries east of the Hills, the Cheyenne River flows eastward to enter the Missouri River north of Pierre, South Dakota.

Numerous secondary tributaries of the Belle Fourche and the Cheyenne South Fork flow eastward from the Hills. Detailed studies were made of deposits of three of these tributaries: (1) Bear Butte Creek, which drains the Tertiary intrusive area of the northern Hills, (2) Rapid Creek, which drains the metamorphic area in the central Hills, (3) Battle Creek, which drains the southern granitic area.

PREVIOUS STUDIES

Prior to 1929 few attempts had been made to unravel the Cenozoic history of the area. The occurrence of high-level Tertiary gravels within the Hills and on the plains to the east was noted by Newton and Jenney (1880, p. 44), Crosby (1882, pp. 516–517), Todd (1900, pp. 120–121), and Darton (1909, pp. 58–59). Newton, Todd, and Darton also mention the presence of Quaternary terraces within the eastern foothill belt and along the tributaries of the Cheyenne River. These accounts are limited to short descriptions of the various terraces, with no attempt at regional interpretation.

Fillman (1929, pp. 1–48) attempted to integrate these terraces into a logical history of development. Three gravel-covered terraces were recognized and named: Mountain Meadow (Tertiary), Rapid (Quaternary), and Sturgis (Quaternary).

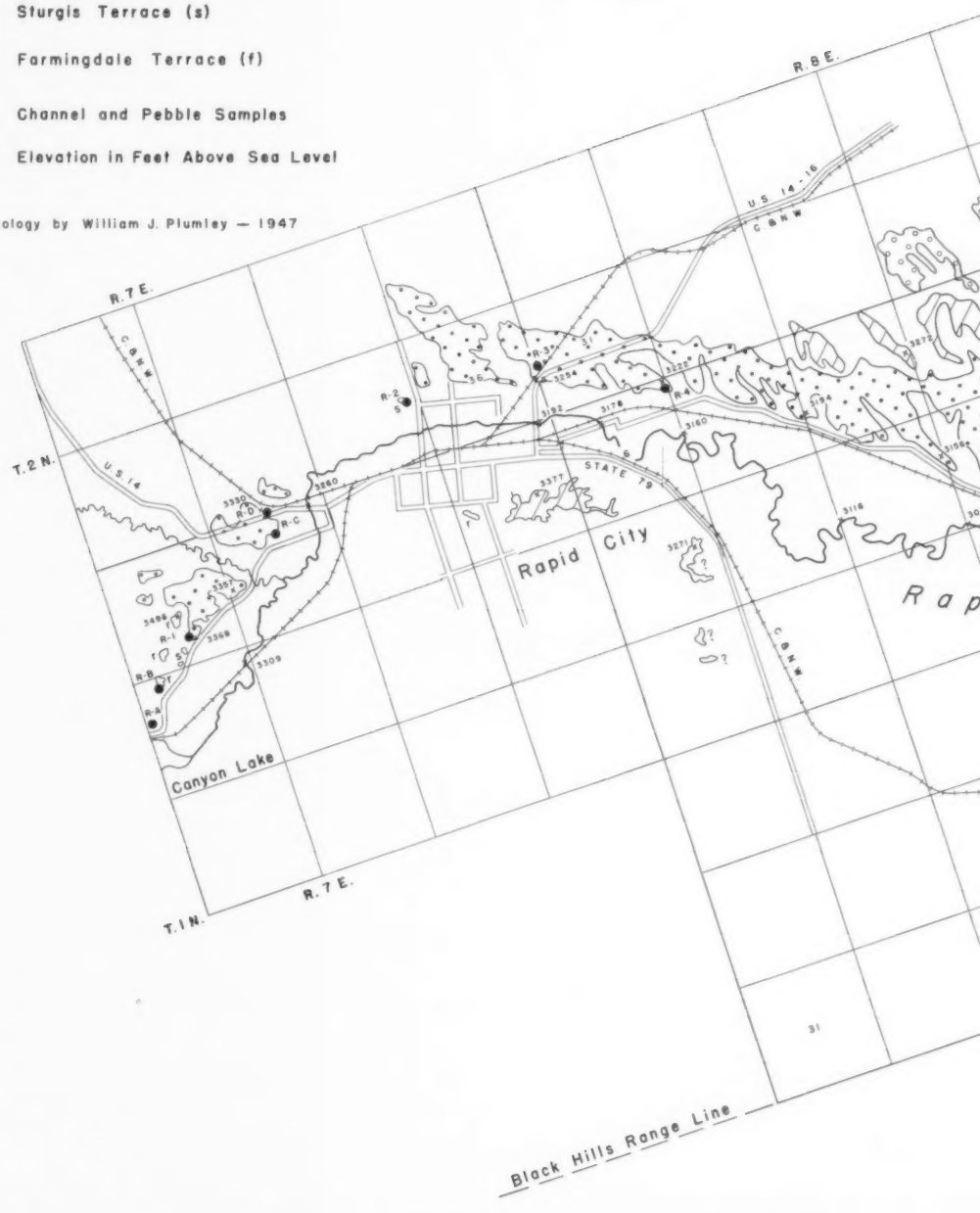
The Mountain Meadow surface is described by Fillman as having a late mature topography with local relief 1,000–1,500 feet within the Hills. The type locality is the Mountain Meadow upland, 1½ miles east of Deadwood. The Mountain Meadow surface is widely distributed in the interior basin and occurs as flat-topped divides on the interstream areas of the adjacent plains east of the Hills. Mountain Meadow time was believed to be brought to a close in mid-Oligocene by differential uplift, which amounted to 2,000–3,000 feet in the central Hills, 250 feet in the foothills, and 20–30 feet in the Big Badlands to the east. This uplift resulted in dissection of the Mountain Meadow surface to form the present valleys within the Hills. At the same time a peneplain was believed to have developed on the plains to the east.

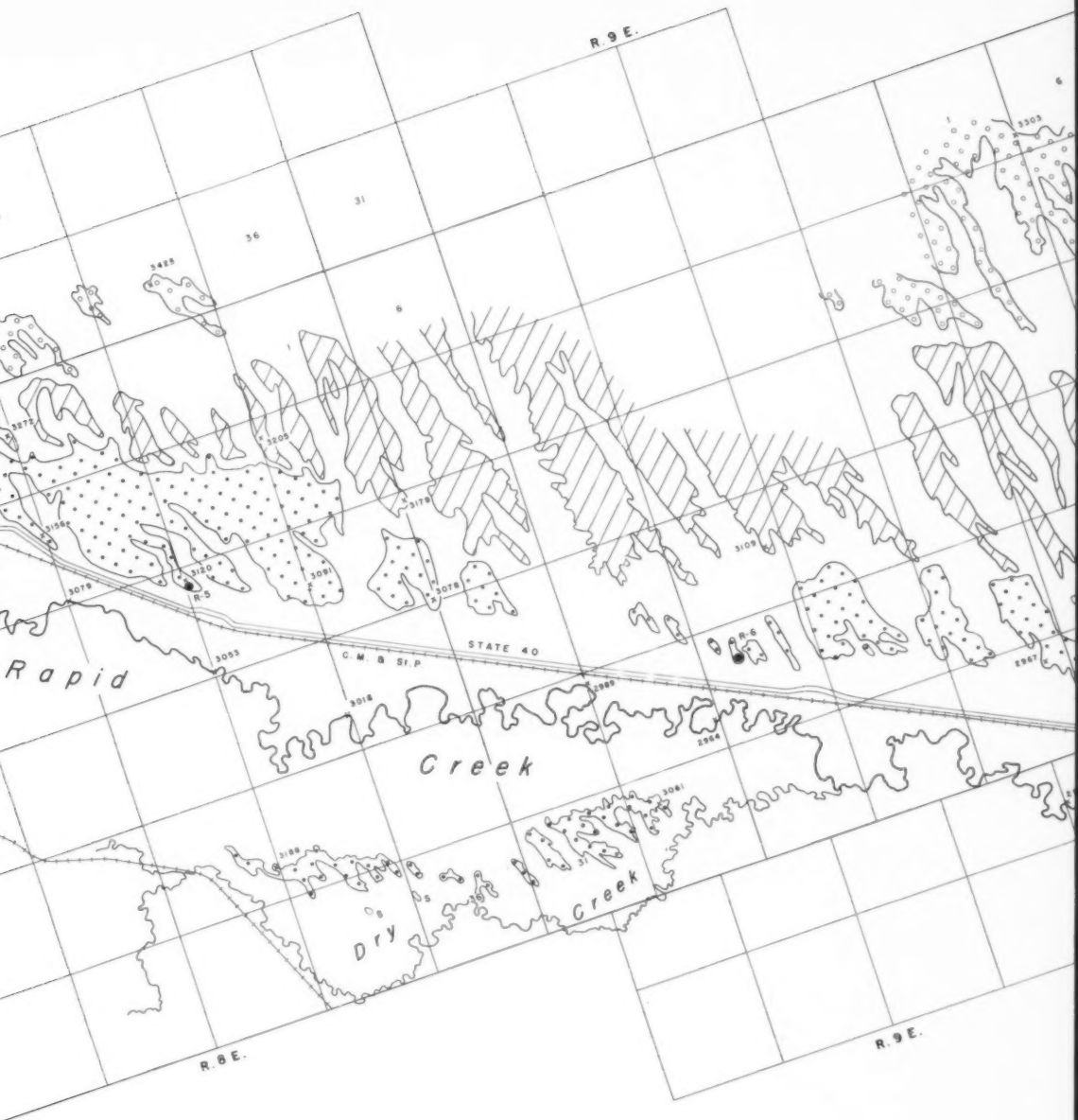
The name "Rapid" was given to the highest gravel-capped terraces along the valleys within the foothills. The type locality is Rapid Creek Valley. Fillman (1929, p. 37) describes the relation between the Mountain Meadow surface and the Rapid terrace as follows: "When the so-called Upper Terrace (Rapid) is traced from the Hills proper it is found to cut across the Mountain Meadow surface on the Plains." As measured by Fillman, the height of the Rapid terrace above drainage on the border of the Hills was found to be 100 ± 5 feet. At the end of Rapid cycle time, the streams began to degrade their valleys once more, leaving the Rapid deposits exposed as gravel-capped terraces. This resumption of

LEGEND

- Mountain Meadow Surface (mm)
- Rapid Terrace (r)
- Sturgis Terrace (s)
- Farmingdale Terrace (f)
- ● R-1 Channel and Pebble Samples
- × 3280 Elevation in Feet Above Sea Level

Geology by William J. Plumley — 1947




R.9E.
31
36
6
1
3425
3303
3275
3205
3178
3109
3156
3120
3081
3078
3079
R-5
R-6
C.M.&St.P.
STATE 40
3033
3016
2980
2964
2967
Rapid
Creek
3041
3188
Dry
Creek
R.8E.
R.9E.

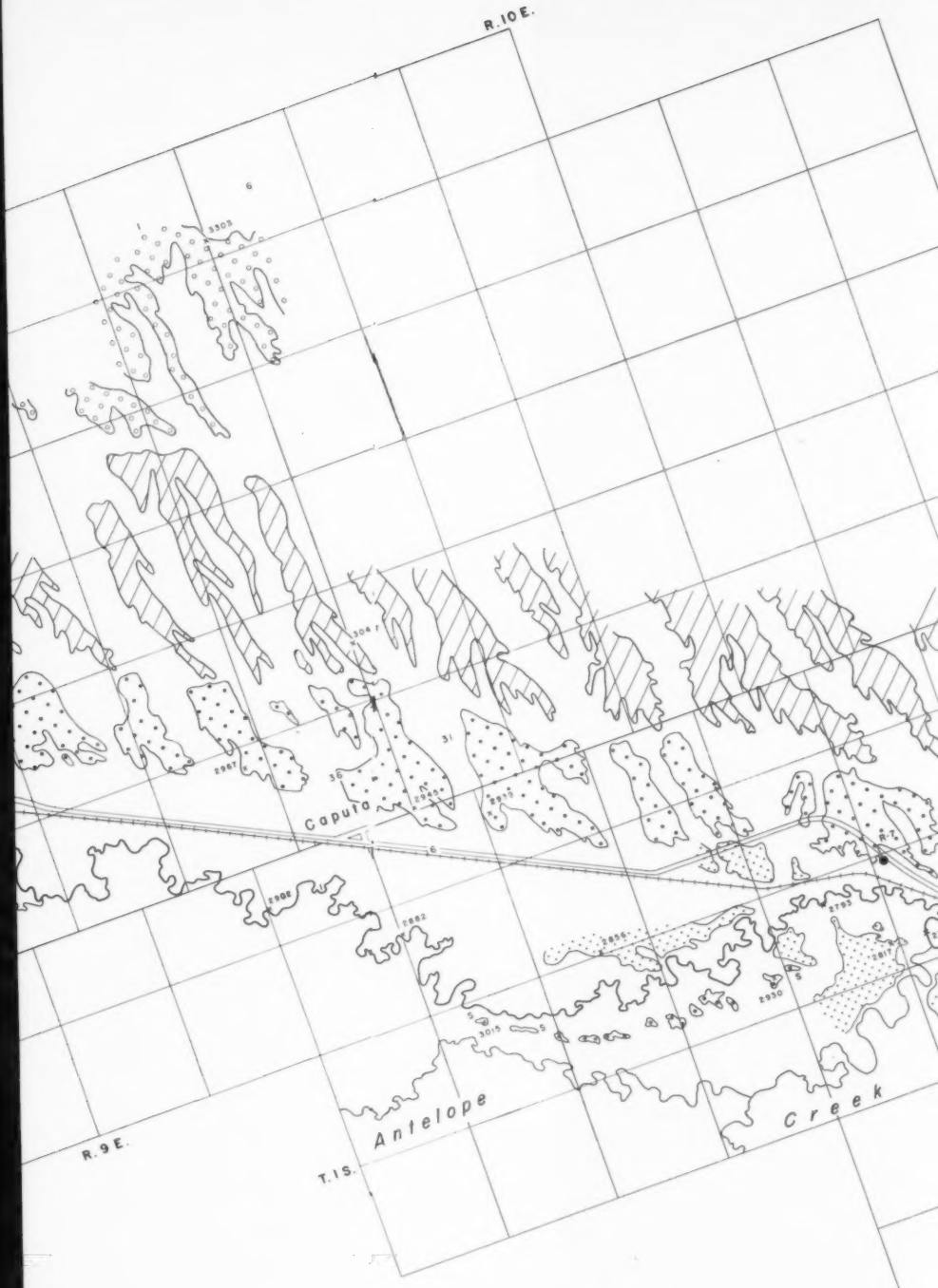
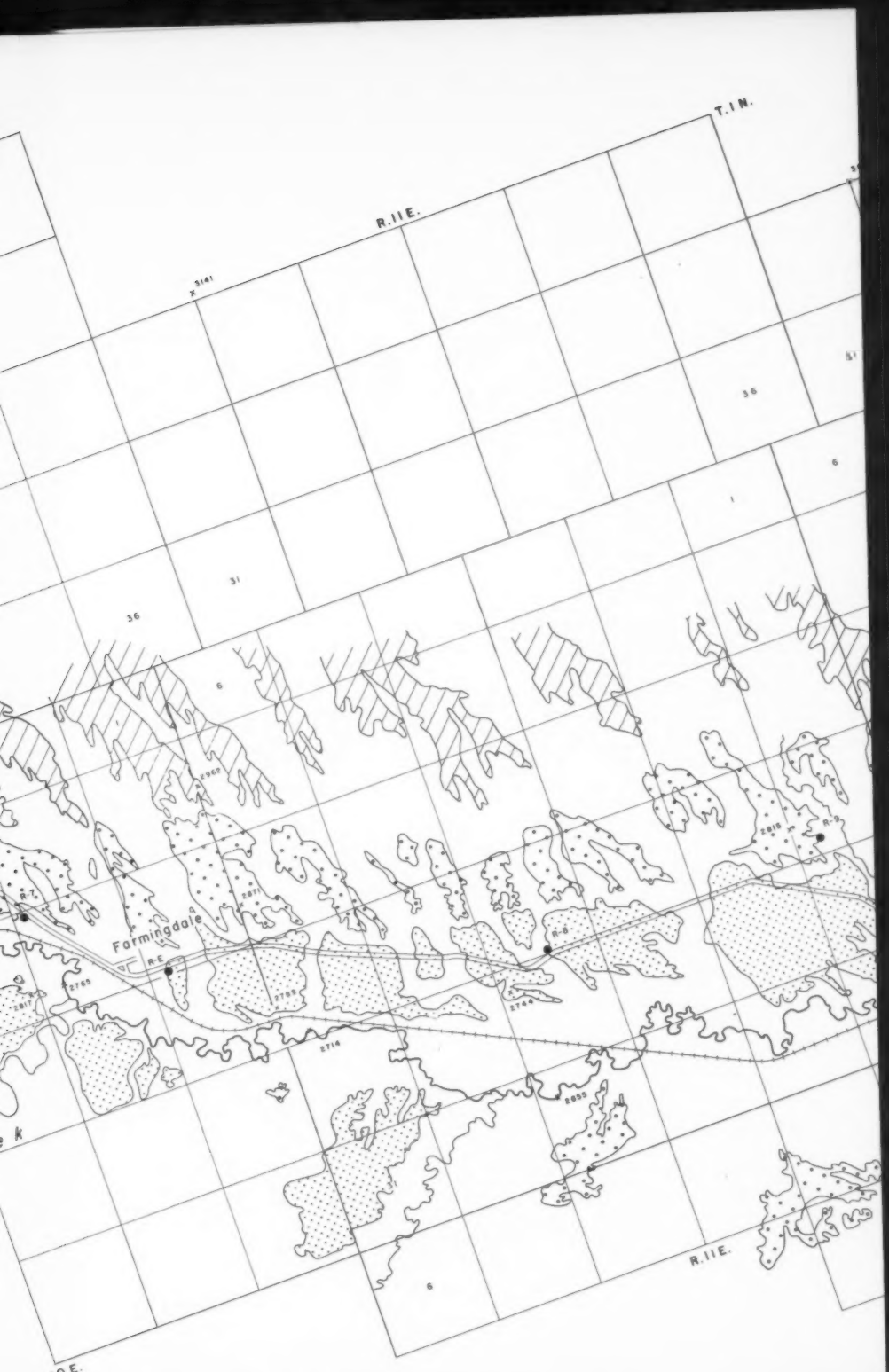
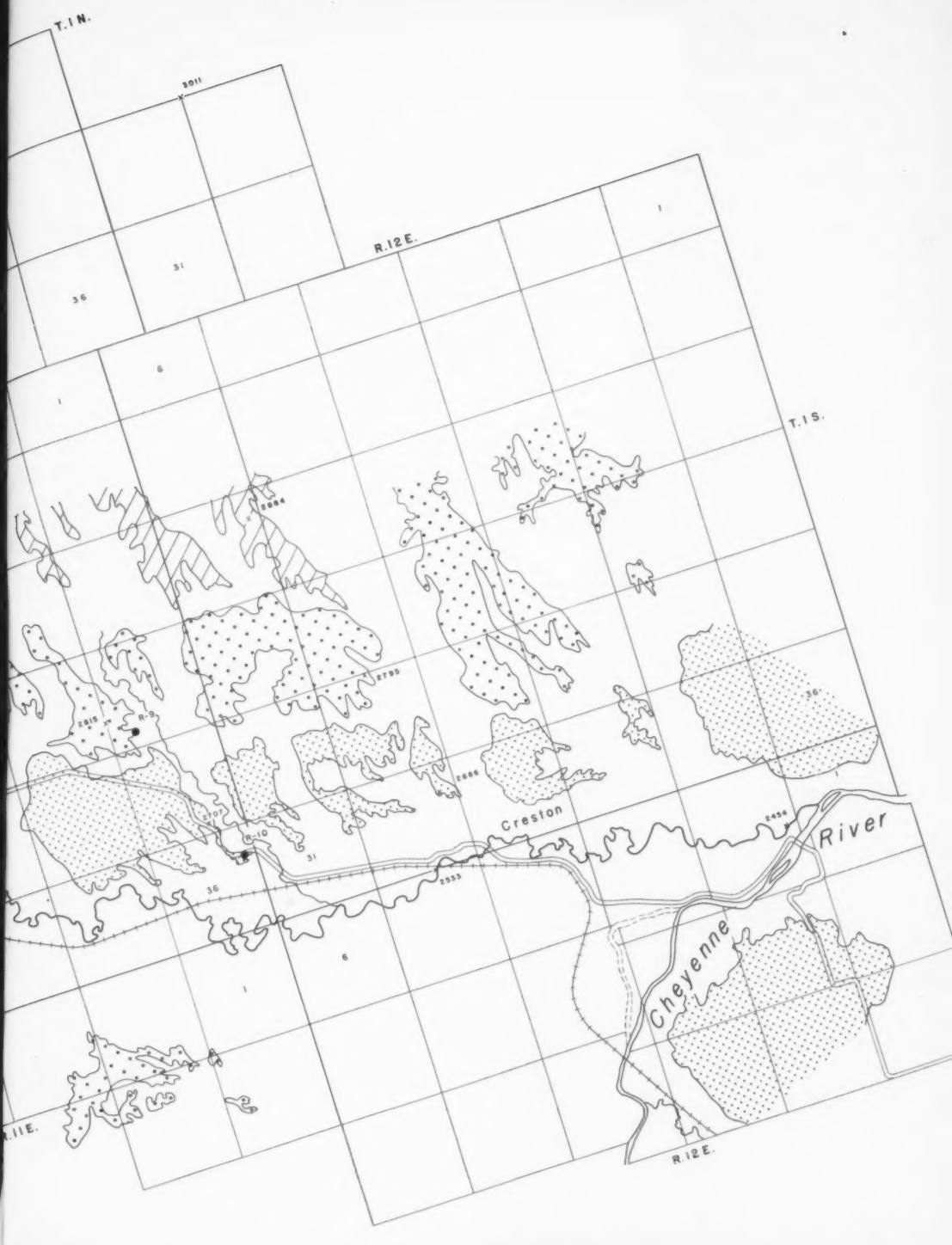


FIG. 2.—Terraces of Rapid Creek Valley


T.1N.
R.11E.
R.10E.
R.11E.
3141
36
31
6
1
5
Farmingdale
R-7
R-6
R-5
R-4
2962
2827
2765
2817
2759
2714
2748
2815
2830


T.1N.
R.12E.
T.1S.
R.11E.
R.12E.
3011
2984
2793
2818
R-9
2686
2707
R-10
2454
2533
Creston
River
Cheyenne

stream downcutting is thought by Fillman to be related to the glaciation of eastern South Dakota or to other climatic changes.

The name "Sturgis" was given to those terraces which are found below the Rapid terrace in all the streams draining the Hills. The town of Sturgis is the type locality. The Sturgis terrace, as measured by Fillman, was found to occur about 50 feet above the present flood plains and consequently about 50 feet below the Rapid terrace level.

FIELD WORK

The field work was greatly facilitated by use of aerial photographs. The photos were examined stereoscopically, and all visible terrace and flat high-level surfaces were outlined. The terrace outlines were verified by reconnaissance. Profiles of Bear Butte, Rapid, and Battle creeks and their terraces were made by means of a Wallace and Tiernen Sensitive Altimeter. The profile of each terrace was constructed with the stream profile as reference level. The final terrace maps were prepared from the aerial photographs by means of the slotted-template method (Kelsh, 1940, pp. 1–49) and vertical Sketchmaster.

Analysis of the field data reveals certain fundamental differences between the physiographic interpretation presented by Fillman and that of the present work. These differences are described in detail in the following section.

DESCRIPTION OF TERRACE SYSTEMS

GENERAL STATEMENT

The most striking feature of the streams flowing eastward out of the Black Hills is the asymmetrical form of their north-south profiles. This feature is readily seen on the topographic maps of the Rapid and Hermosa quadrangles. The southern slopes of the majority of the creek valleys are very steep compared to the gentle northern slopes. Bear Butte and Rapid creeks possess this attribute to a high degree, and, as a result, terraces are commonly found on the northern sides of their valleys.

To avoid confusion in nomenclature, the names given to various surfaces by Fillman have been kept, even though considerable revision of heights and locations of these surfaces is necessary. In addition to the Mountain Meadow, Rapid, and Sturgis surfaces, two other terraces were found.

RAPID CREEK

In figure 2 four erosional surfaces are mapped. The outlines of these surfaces represent the relatively flat areas only. The highest surface is the Mountain Meadow, which is found topping the divide between Rapid Creek and Boxelder Creek to the north. At the first two elevation points on the Rapid Creek profile (fig. 3) this high surface occurs as a flat area whose outlines can be mapped. The two elevation points farther to the east represent the highest points on the divide between Rapid and Boxelder creeks. These latter points are considered to be below the Mountain Meadow surface, because joining them with the first two elevation points forms a convex profile, which means that subsequent erosion has removed the Mountain Meadow surface from the drainage divide a few miles east of the Hills.

The next lower surface is the Rapid terrace, which in the vicinity of Rapid City is at an elevation of 180 feet above Rapid Creek. This elevation is 80 feet higher than the one given by Fillman. One remnant of this terrace is found in

the Red Valley west of Rapid City. The next remnant to the east forms an elevated and steep-sided flat within Rapid City. As it is traced eastward, the Rapid terrace becomes wider, and its boundaries away from the stream are less distinct. East of Rapid City it is found exclusively on the north side of Rapid Creek. Nevertheless, Fillman mapped the Rapid terrace on both sides of Rapid Creek. The terrace remnants south of Rapid Creek, however, are related to creeks tributary to Rapid Creek and not to Rapid Creek itself.

The Sturgis terrace is present throughout Rapid Creek Valley. Near Rapid City it is about 60 feet above drainage. Like the Rapid terrace, it is found predominantly on the north side of the valley. Two conspicuous terrace systems are found on the south side of the valley, which are related to the Sturgis cycle but are not at the same elevations. These terraces are located between Dry Creek and Rapid Creek and between Antelope Creek and Rapid Creek. Reference to the profile (fig. 3) reveals that the gradients of these terraces are related neither to the gradient of Rapid Creek nor to those of its terrace systems. On the contrary, it is probable that these terraces represent former stream flats of Dry and Antelope creeks. The lower end of each of these terraces appears to merge with the Sturgis terrace of Rapid Creek. Therefore, they probably represent the levels of Dry and Antelope creeks during Sturgis cycle time. These terraces which border Rapid Creek on the south and yet are not directly related to it are evidence that at the time of their formation Rapid Creek must have been located farther north than it now is. At that time a divide must have existed between Rapid Creek and the two tributaries. Later southward migration of

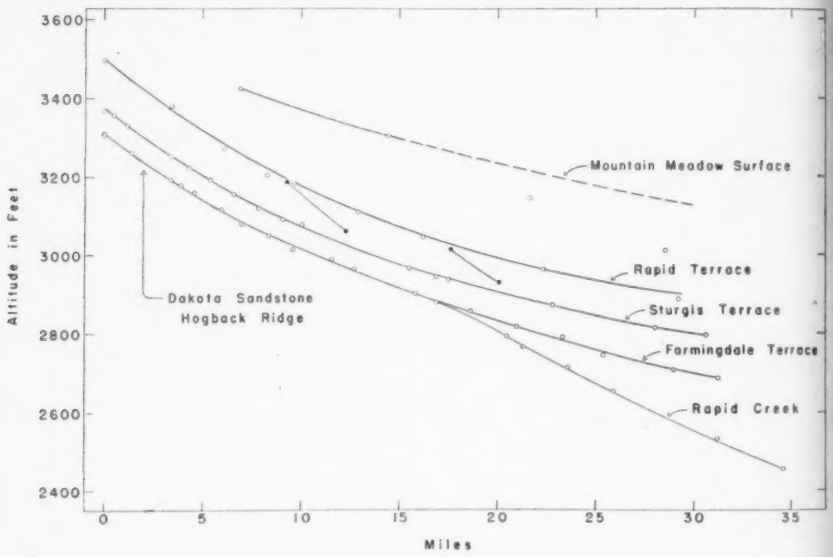


FIG. 3.—Rapid Creek profile

LEGEND

- Rapid Terrace (r)
- Sturgis Terrace (s)
- Bear Butte Terrace (bb)
- Farmingdale Terrace (f)
- ● BB-1 Channel and Pebble Samples
- × 3250 Elevation in Feet Above Sea Level

Geology by William J. Plumley — 1947

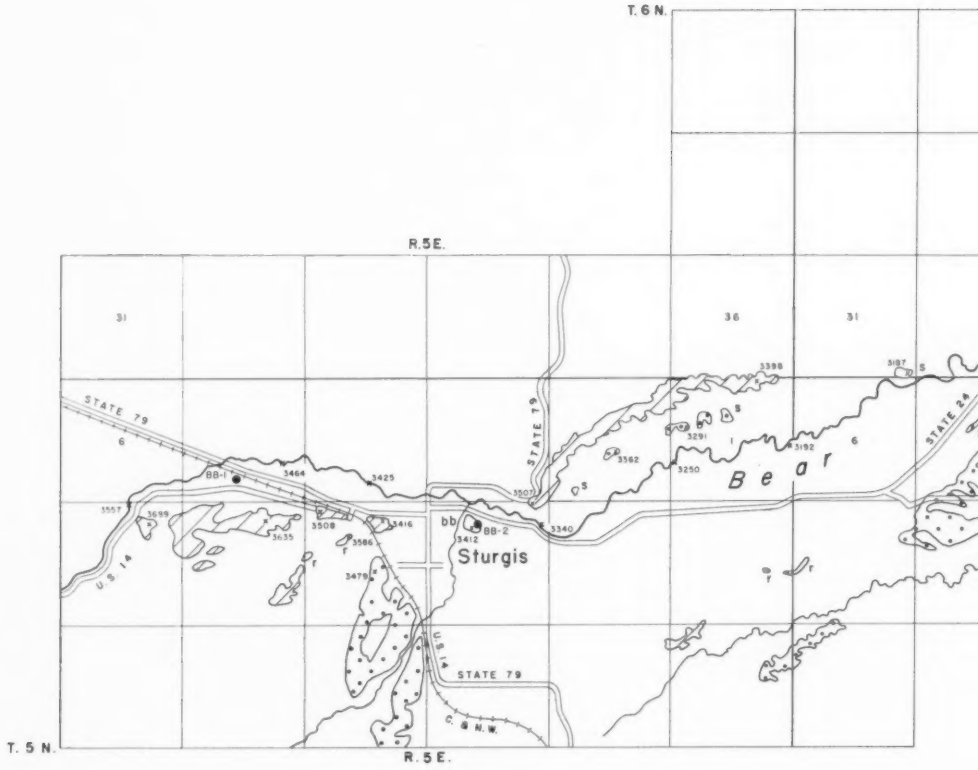
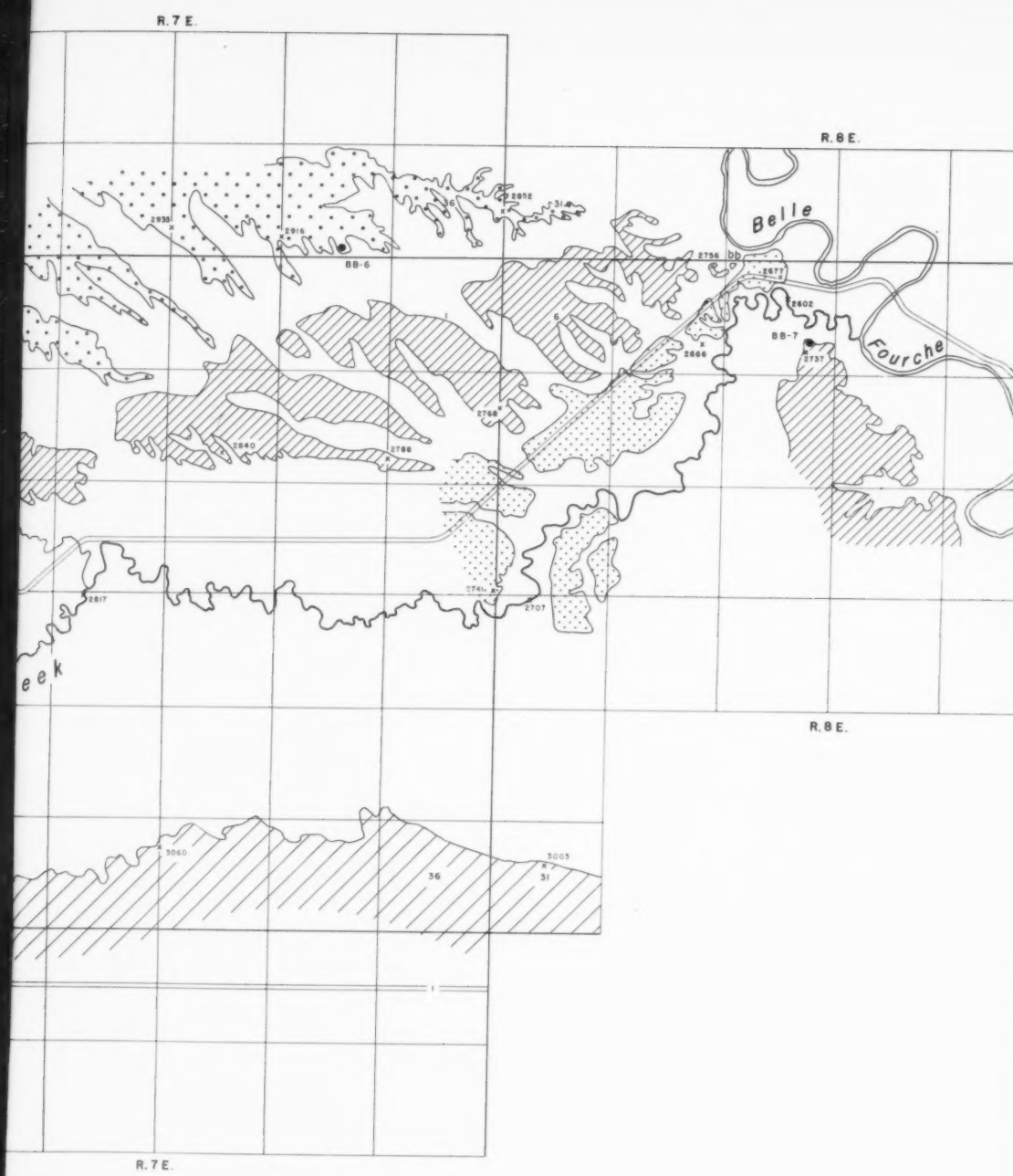
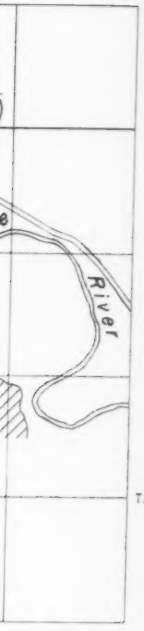


FIG. 5.—Terraces of Bear Butte Creek Valley


R. 7 E.
R. 8 E.
Belle
Fourche
BB-6
BB-7
2938
2916
2932
2756
bb
2677
2602
2737
2666
2768
2840
2788
2741
2707
2817
eek
3060
3003
36
31
6
R. 7 E.
R. 8 E.


River
T. 6 N.

Rapid Creek removed all trace of that divide, with the exception of one remnant of higher ground between Rapid Creek and the terrace of Dry Creek. In figure 4 these relations are shown diagrammatically. The block diagram pictures the condition existing during the Sturgis cycle. The dashed lines represent the present conditions resulting from southward migration of Rapid Creek in post-Sturgis time.

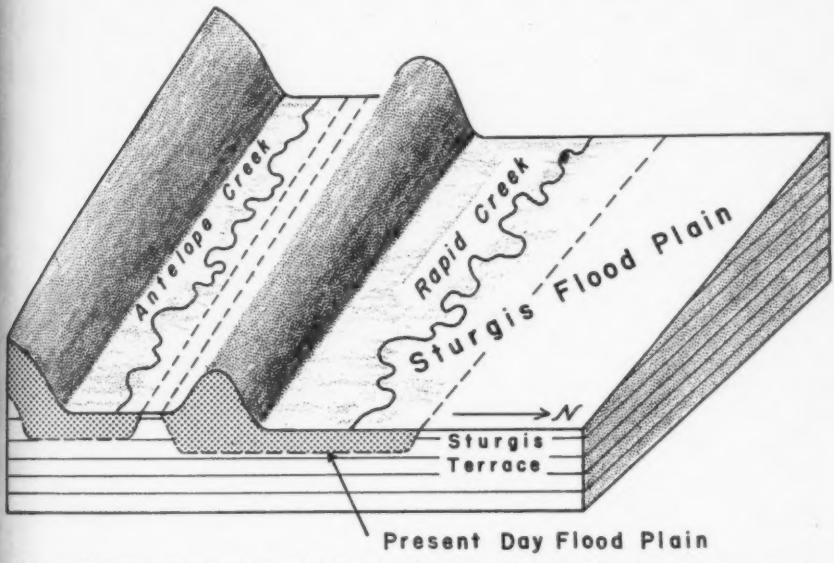


FIG. 4.—Diagrammatic sketch of probable land surface in Rapid Creek Valley during the Sturgis cycle

A fourth, hitherto unknown, terrace system was found in Rapid Creek Valley. It is named the "Farmingdale terrace" because of its inception near the Farmingdale railroad stop. It appears in Rapid Creek Valley only between Farmingdale and the Cheyenne River. West of Farmingdale it coincides with the present-day flood plain of Rapid Creek. Reference to the profile (fig. 3) reveals that this terrace owes its presence to a marked increase in the gradient of Rapid Creek east of Farmingdale. The Farmingdale terrace is conspicuous along the Cheyenne River.

One other terrace should be mentioned to complete the record. It lies about 2 miles southeast of Rapid City and trends north-south at an elevation intermediate between the Rapid and the Sturgis terraces. It was not possible on the available field evidence to correlate this terrace with those of the other creeks studied.

BEAR BUTTE CREEK

The terraces of Bear Butte Creek, with a few important exceptions, are similar to those of Rapid Creek. The Rapid and Sturgis terraces are present, but the Mountain Meadow surface is absent. In addition, there are two terraces below the Sturgis level (figs. 5 and 6).

The highest level is the Rapid terrace, which in the vicinity of the town of

Sturgis is 170 feet above drainage (according to Fillman, 100 feet). Unlike the Rapid terrace along Rapid Creek, which continues as a distinct terrace many miles east of the Hills, the Rapid terrace along Bear Butte Creek occupies an interstream divide a few miles east of Sturgis. As may be seen in figure 5, the Rapid surface occupies the highest land between Bear Butte Creek and Alkali Creek to the south. Fillman mapped this surface as Mountain Meadow. The profile (fig. 6) shows this to be incorrect as this stream-divide area is a direct continuation of the Rapid terrace closer to the Hills.

Within the foothill belt near the town of Sturgis, the Sturgis terrace occurs 70 feet above drainage. East of Bear Butte the Sturgis terrace merges with the plains surface north of Bear Butte Creek. Because of the asymmetry of the valley, however, this plains surface is considerably below the Rapid surface south of the creek. Fillman mapped this area north of Bear Butte Creek as the Mountain Meadow surface. However, the Sturgis terrace profile shows this plains area to be merely a continuation of the Sturgis terrace.

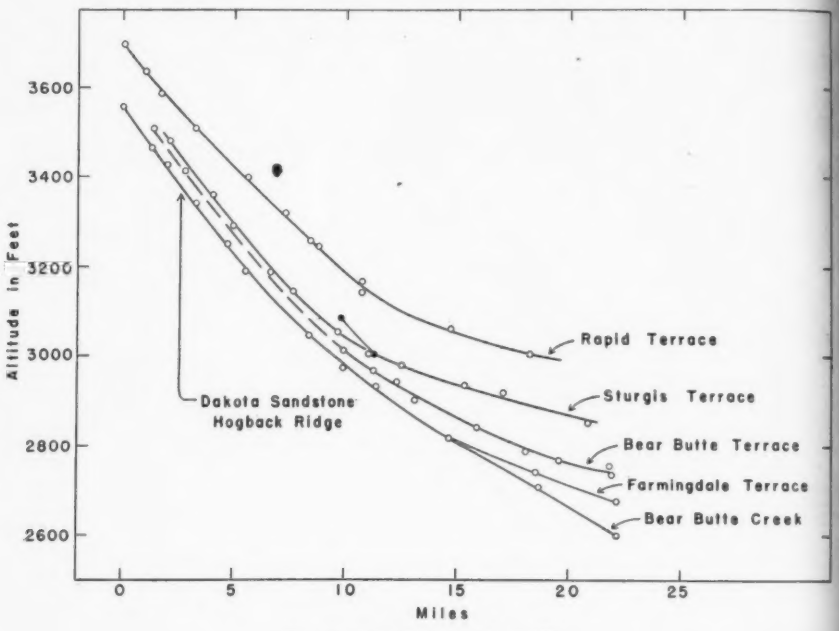
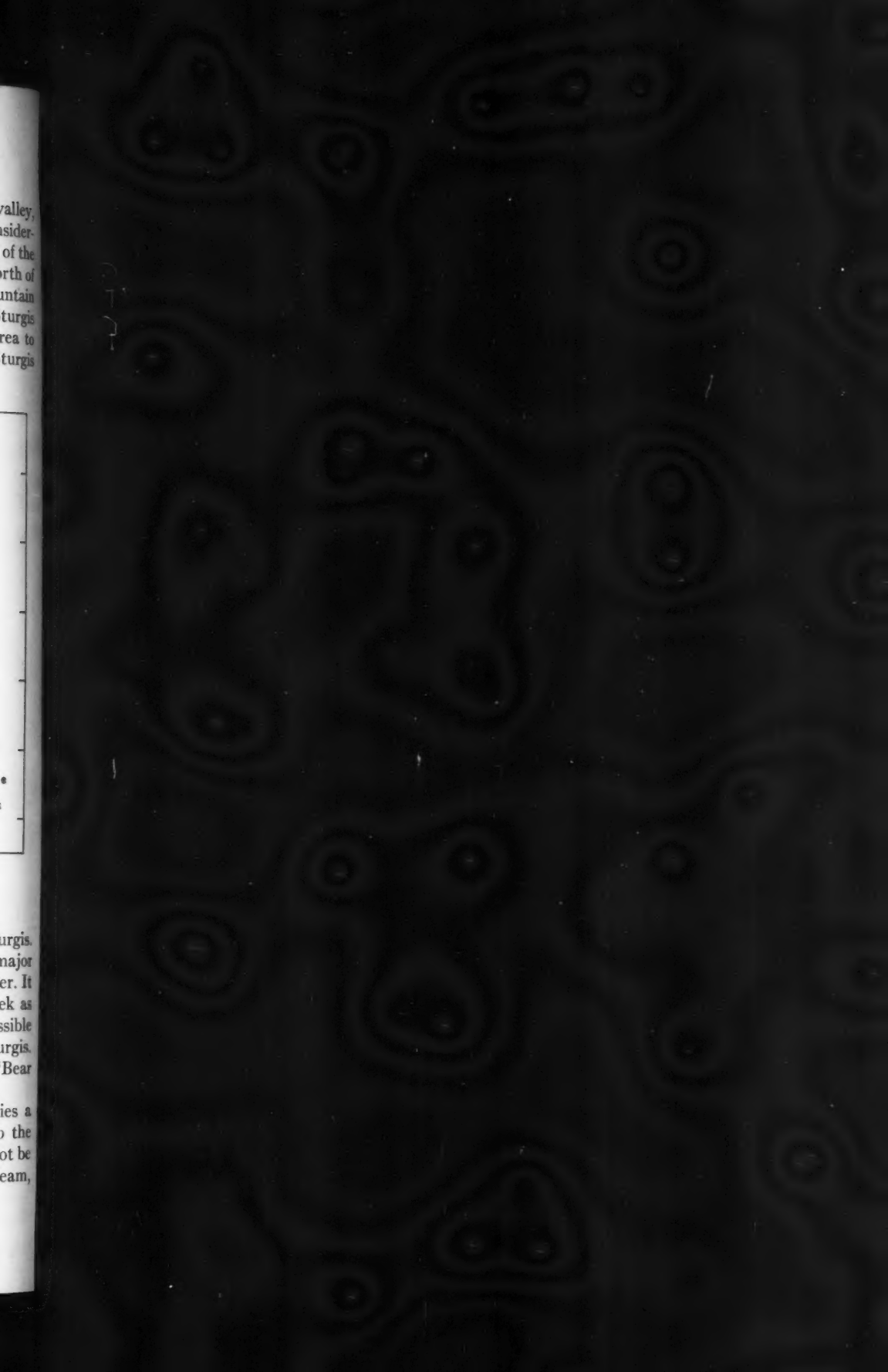
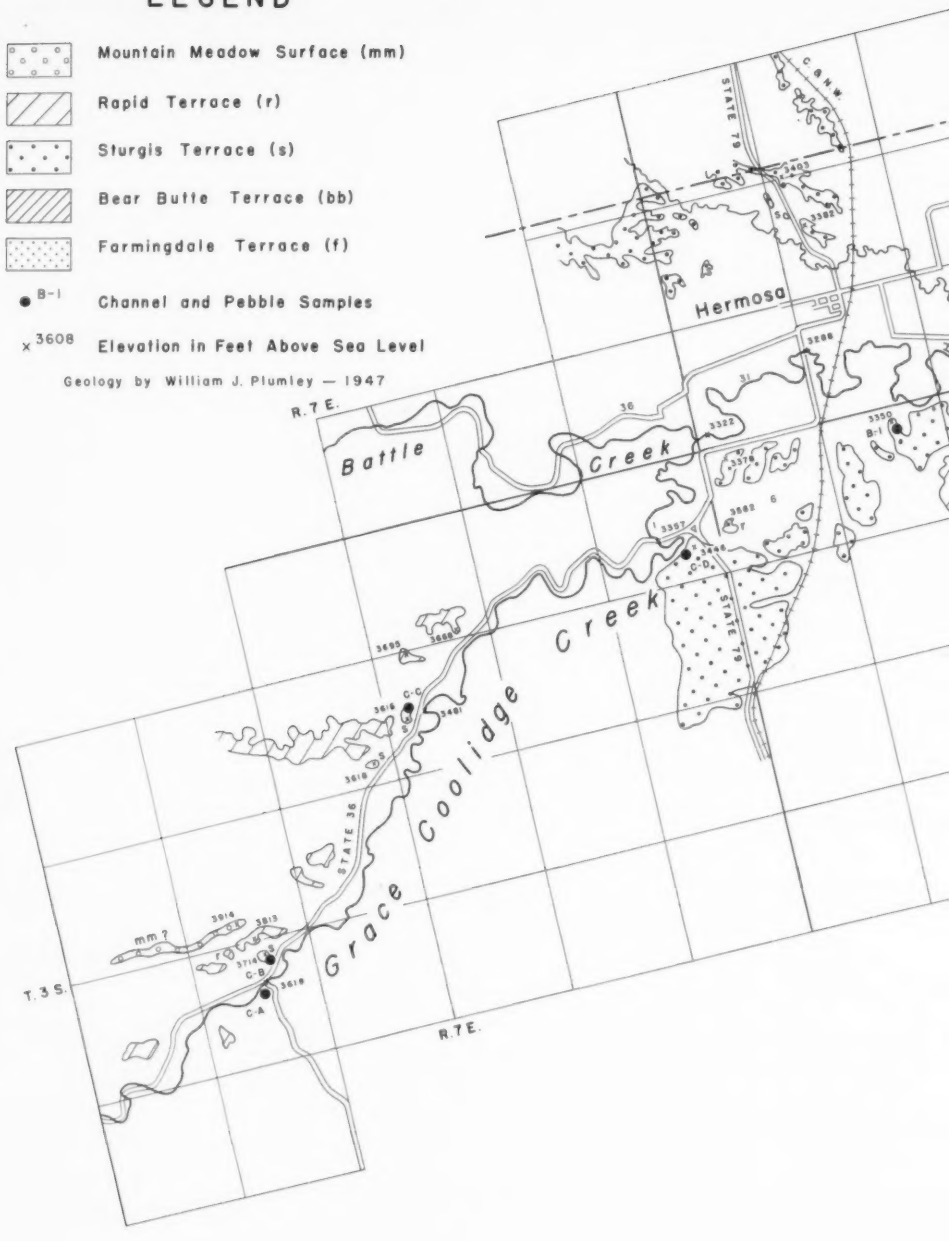


FIG. 6.—Bear Butte Creek profile

Two terraces occur below the Sturgis. The highest of these occurs as a major terrace along the Belle Fourche River. It is prominent along Bear Butte Creek as far west as Bear Butte. A few possible remnants are detectable near Sturgis. This terrace is here named the "Bear Butte terrace."

Below the Bear Butte terrace lies a fourth terrace, which is confined to the lower portion of the valley and cannot be traced west of a knickpoint in the stream,




LEGEND
Mountain Meadow Surface (mm)
Rapid Terrace (r)
Sturgis Terrace (s)
Bear Butte Terrace (bb)
Farmingdale Terrace (f)
B-1 Channel and Pebble Samples
x 3608 Elevation in Feet Above Sea Level
Geology by William J. Plumley — 1947
R.7 E.
Battle Creek
Hermosa
Grace Coolidge Creek
STATE 79
STATE 36
C & N.W.
T. 3 S.
R.7E.
mm?
C-A
C-B
C-C
C-D
B-1

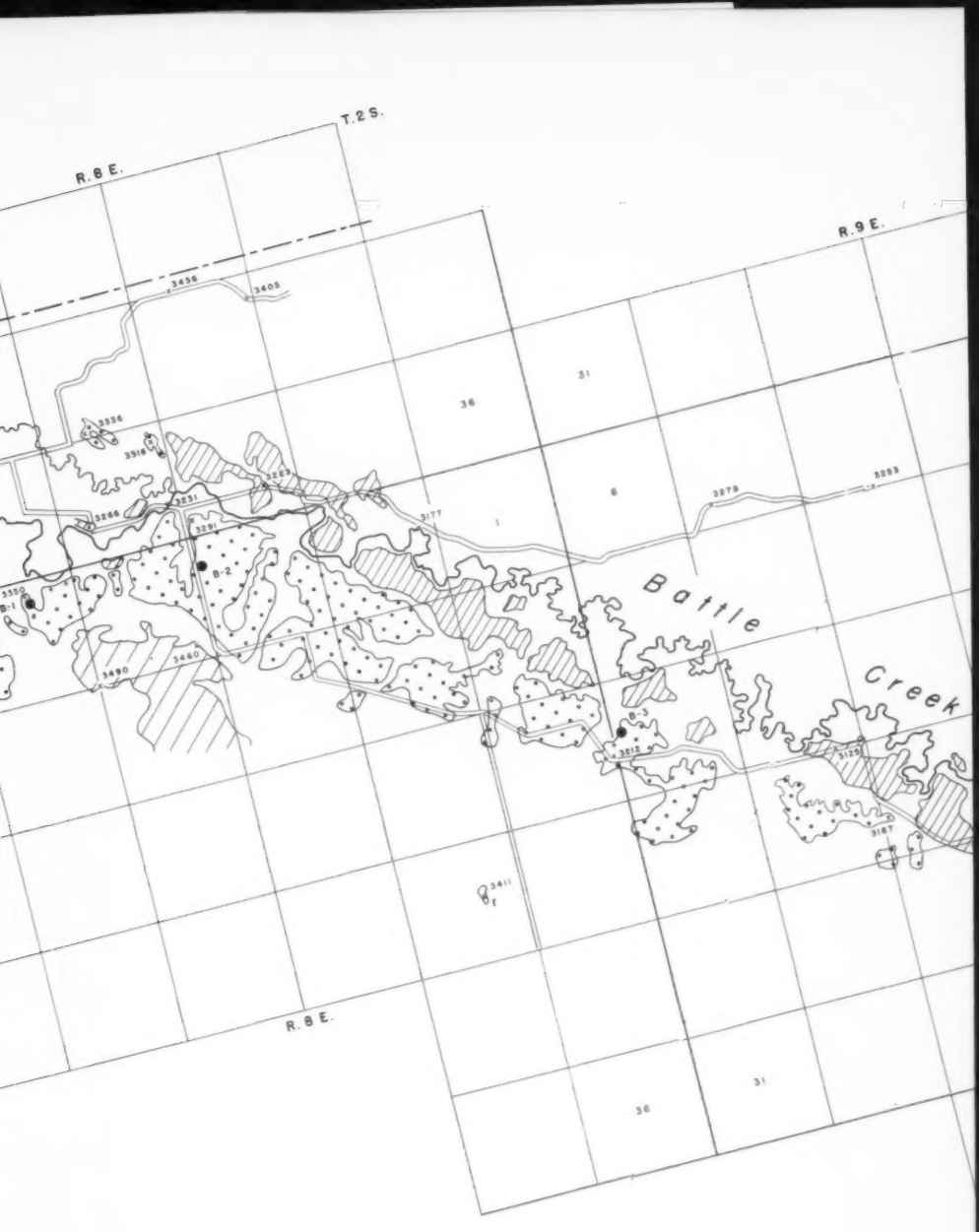
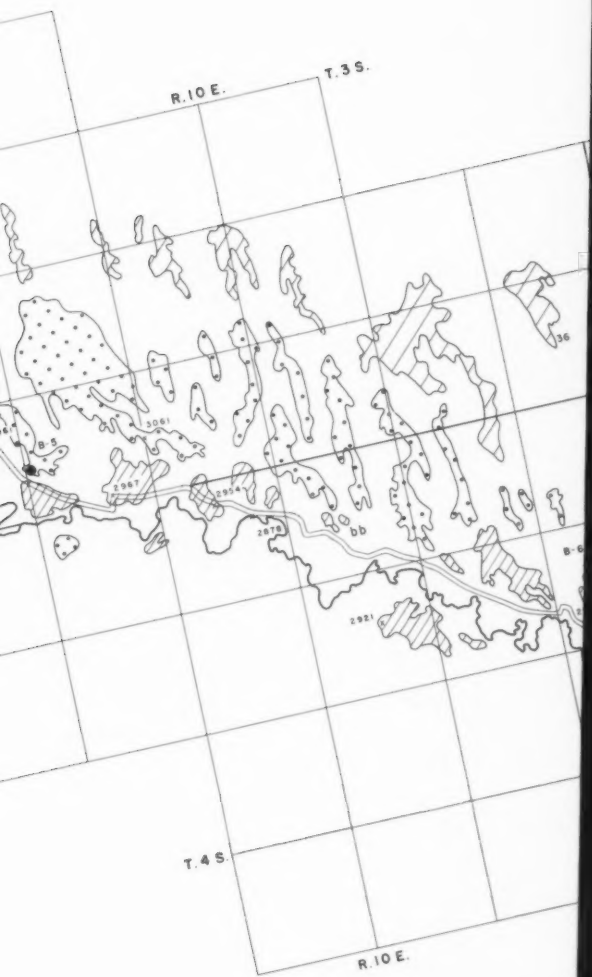
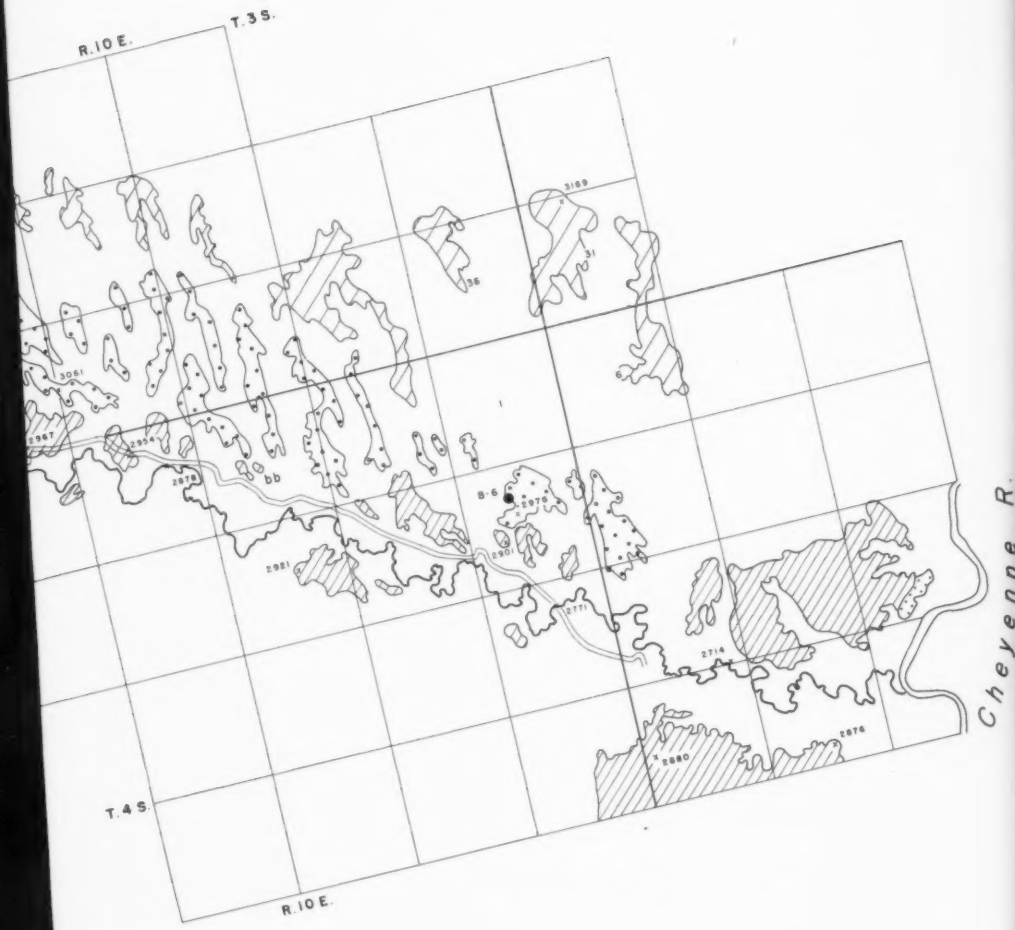


FIG. 7.—Terraces of Battle Creek Val

of Battle Creek Valley


R.10 E.
T.3 S.
B-5
3061
2967
2954
2878
bb
2921
36
T.4 S.
R.10 E.


R.10E.
T.3S.
3169
31
36
3061
2987
2904
2878
bb
B-6
2976
2901
2771
2981
2714
2880
2876
Cheyenne R.
T.4S.
R.10E.

Cheyenne R.

at which place it appears to merge with the present-day flood plain. It is tentatively correlated with the Farmingdale terrace of Rapid Creek Valley.

An anomalous terrace occurs between Bear Butte and Bear Butte Creek. Its eastern extremity merges with the Sturgis terrace between Bear Butte and Spring creeks. Its western end merges with the talus slopes of Bear Butte. This surface is apparently a remnant of a previously more extensive alluvial fan of Bear Butte.

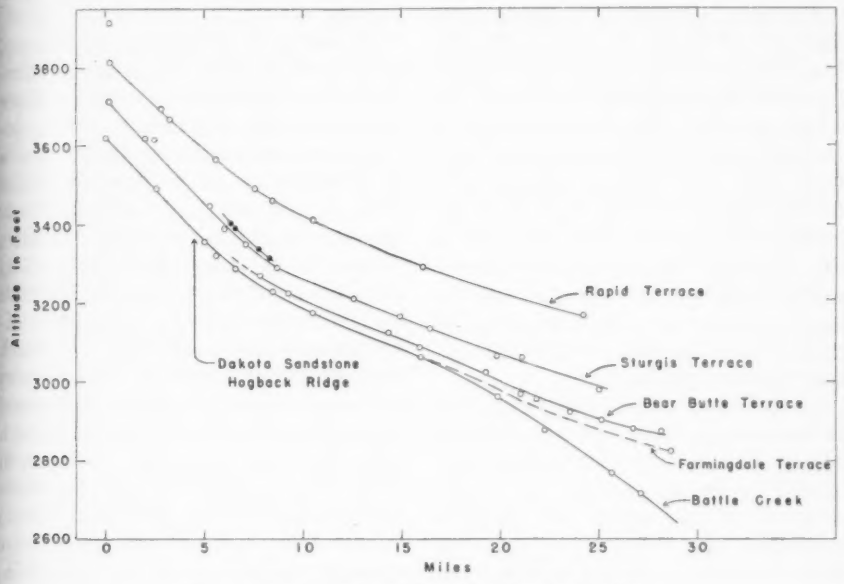


FIG. 8.—Battle Creek and Grace Coolidge Creek profile

BATTLE CREEK

The Rapid cycle is represented in Battle Creek Valley by both terraces and interstream divides. Remnants of the Rapid terrace can be traced several miles west of Hermosa up the valley of Grace Coolidge Creek (figs. 7 and 8). Near the town of Hermosa the Rapid terrace occurs 230 feet above drainage. Little correlation was noted between its location as reported by Fillman and as found by the writer. South of Battle Creek the Rapid terrace appears as a bench extending about 1½ miles east of Hermosa. East of this point it gives way to higher ground, capped by resistant Tertiary conglomerate. About 10 miles southeast of Hermosa the Rapid terrace is found on the north side of the valley. In this area the Rapid surface forms the divide between Battle Creek and Spring Creek to the north.

Remnants of the Sturgis terrace extend several miles up Grace Coolidge Creek. It can be traced eastward from Hermosa to the Cheyenne River.

Thirteen miles southeast of Hermosa the gradient of Battle Creek suddenly steepens (fig. 8). Upstream from this knickpoint a low terrace is traceable westward almost to Hermosa. In places

this terrace almost fills the valley. The terrace extends downstream from the knickpoint and is widespread in the Cheyenne River Valley. It is tentatively correlated with the Bear Butte terrace of Bear Butte Creek Valley.

The Farmingdale terrace is absent along Battle Creek. It is present, however, along the Cheyenne River near the mouth of Battle Creek.

Two anomalous surfaces appear along Battle Creek Valley. In T. 3 S., R. 9 E., S. 28 a gravel-capped butte was found at an elevation intermediate between the Rapid and the Sturgis terraces. It is capped by about 6 feet of gravel lying upon a layer of Tertiary conglomerate. Perhaps during the Sturgis cycle, downcutting was retarded when the level of this resistant conglomerate was reached. Battle Creek later cut down through this hard layer and has since removed all trace of it, with the exception of one gravel-capped remnant.

On the north side of Battle Creek, east of Hermosa, is a large, relatively flat area intermediate in height between the Rapid and the Sturgis terraces. Gravel was observed on this surface near elevation point 3,405. The writer is unable to state without further evidence whether this surface has regional significance or is peculiar to the Battle Creek area only.

At the head of Grace Coolidge Creek an elongated gravel-capped flat was found about 100 feet above the Rapid terrace. This surface may possibly be the Mountain Meadow.

HISTORY OF THE TERRACE CYCLES

During and following the uplift of the Black Hills in the Laramide revolution the area was subjected to erosion. No Eocene deposits are present in the area; either they were never deposited or they were removed prior to Oligocene deposition. The Oligocene White River group (Chadron and Brule formations) is a fluviatile and lacustrine deposit. The presence of basal conglomerates in the Chadron formation (Lower White River) indicates moderate relief in the Hills in early Oligocene time. The generally fine texture of the overlying White River deposits indicates deposition by streams of gentle gradient and in local lakes or bayous.

According to Darton (1899–1900, p. 561), the Hills were uplifted several hundred feet subsequent to White River deposition. Material from the Hills contributed to the coarser fluviatile deposits of Miocene age which cap the White River deposits south of the White River. Wanless (1923, pp. 190–269) considers Miocene beds capping White River beds on isolated buttes northeast of the Hills evidence that Miocene sediments extended east and northeast of the Black Hills as well as southeast. He concludes that a period of peneplanation followed Miocene or Pliocene deposition, in which beds of the same age were eroded more in South Dakota than in Nebraska. Remnants of this surface (the High Plains) exist as table tops and cut across Pierre shale (Cretaceous) on the north and Miocene sediments on the south. Fenneman (1931, pp. 61–79) states that Pliocene sediments (Ogallala formation) were being deposited in Nebraska at the same time that erosion was proceeding to the north in South Dakota. He therefore dates the High Plains surface as Pliocene. Degradation continued subsequent to the formation of this erosion surface in South Dakota, so that today it exists only as isolated flat-topped buttes north of the Pine Ridge escarpment.

These regional features must be considered in discussing the age of the Mountain Meadow surface. Fillman

(1929, pp. 1–48) contends that the Mountain Meadow surface was produced in mid-Oligocene time, following deposition of the Chadron formation. She states that, before deposition of the Brule formation (Upper Oligocene), the Mountain Meadow surface was uplifted 2,000–3,000 feet in the Hills and 20–30 feet in the Big Badlands. Her evidence for the age of this surface is (1) the mid-Oligocene age of the fossils contained in the gravels which lie upon it and (2) the fact that the Mountain Meadow surface plunges beneath younger materials (Rapid terrace gravels—Pleistocene) a few miles east of the Hills. It is thought to be correlative with the Chadron-Brule unconformity in the Big Badlands.

The writer's field observations are at variance with Fillman's hypothesis for the following reasons: (1) The Mountain Meadow surface as mapped by Fillman represents several cycles of erosion. For example, the stream-divide surface between Bear Butte and Alkali creeks is correlative with the Rapid terrace to the west. The plains surface between Bear Butte Creek and the Belle Fourche River in T. 7 N. and R. 7 E. is correlative with the Sturgis terrace to the west. East of Hermosa large areas of the upland between Battle and Spring creeks have been reduced to lower elevations since the formation of the Rapid surface in the vicinity. Each of these surfaces has been mapped as Mountain Meadow by Fillman. Thus the term "Mountain Meadow surface" loses its genetic significance when applied to the plains area east of the Hills unless its limits can be more rigorously outlined. (2) East of Rapid City the divide between Rapid and Boxelder creeks is flat-topped and gravel-covered. The writer believes that this high surface is correctly identified as the Mountain Meadow surface and is correlative with the subsummit surface of that name in the Hills. The west-east profile of this surface does not intersect the Rapid surface to the east, as contended by Fillman. Therefore, any correlation of the Mountain Meadow surface east of Rapid City with the mid-Oligocene unconformity in the Big Badlands is extremely doubtful.

Darton's report (1899–1900, p. 543) reveals that mid-Oligocene fossils were found in White River deposits high in the Hills southwest of Hermosa. However, this proves nothing about Mountain Meadow age unless these beds can be established as equivalent to gravels capping the Mountain Meadow surface. On the basis of the discrepancies indicated in 1 above, this correlation must be suspect.

The above analysis indicates that neither fossil nor physiographic evidence dates the Mountain Meadow surface as mid-Oligocene. Meyerhoff and Olmstead (1937, p. 306) report that the subsummit erosional surface in the Black Hills was formed contemporaneously with the Miocene depositional surface of the High Plains in southeastern Wyoming and Nebraska (as noted previously, Fenneman assigns a Pliocene age to the High Plains). They point out that earlier studies have argued for an Eocene age because White River sediments are found in valleys at elevations distinctly lower than the subsummit level. They contend, however, that the distribution and variable elevations of the White River deposits suggest valley-filling in a more rugged and therefore more ancient country than that represented in the subdued topography of the Black Hills. They conclude, therefore, that the valleys were filled and the interstream divides peneplained simultaneously and that equilibrium between the complementary

processes of degradation and aggradation was achieved in Miocene time.

From the foregoing considerations it is possible to conclude only that the true Mountain Meadow surface, as exemplified by the subsummit surface within the Hills and the Rapid–Boxelder Creek divide east of the Hills, was produced by degradation during Miocene or Pliocene time.

Subsequent to the formation of the Mountain Meadow surface a new cycle of erosion was begun. Deep valleys were excavated within the Hills, and a peneplain surface was developed in the area to the east (Rapid cycle). Close to the Hills the planation was least effective, as shown by the Mountain Meadow surface still preserved on the stream divides.

TABLE 1

CORRELATION OF STREAM TERRACES IN THE BLACK HILLS REGION

Battle Creek	Rapid Creek	Bear Butte Creek
Rapid terrace	Rapid terrace	Rapid terrace
Sturgis terrace	Sturgis terrace	Sturgis terrace
Bear Butte terrace		Bear Butte terrace
	Farmingdale terrace	Farmingdale terrace

During Rapid cycle time the streams flowing east from the Hills did not enter the Cheyenne South Fork as they do today. Todd (1902, pp. 27–40) noted that numerous Black Hills erratics capped extensive areas in the valleys of the White and Bad rivers (inset map, fig. 1) and that shallow, gravel-filled channels crossed the Cheyenne–White River divide, which is at an elevation comparable to that of the Rapid surface to the west. Therefore, Todd concluded that in Pliocene time drainage was eastward from the Black Hills across the present South Fork of the Cheyenne River and that also in later Pliocene time a southward-working tributary of the Cheyenne River captured the headwaters of the White and Bad rivers. Perisho and Visher (1912, pp. 57–58) and Wanless (1923, pp. 190–269) concurred with Todd's findings but placed this series of events in the Pleistocene. This latter conclusion is supported by Fillman's report on the discovery of a Pleistocene horse's tooth in the Rapid terrace gravels.

Following the widespread planation of the Rapid cycle, the streams again resumed downcutting in the Sturgis cycle of erosion. Before the graded condition was reached in this cycle, streams such as Rapid and Battle creeks were integrated into one system by the pirating action of the Cheyenne South Fork. The Sturgis terrace levels are well below the Cheyenne–White River divide, thus placing the time of piracy after Rapid cycle time and before completion of the Sturgis cycle.

Analysis of the physiographic history from the close of the Sturgis cycle to the present is complicated by two other terrace systems which reflect pauses in the reduction of the land. Although two distinct terrace levels below the Sturgis level are present in the valleys of the Belle Fourche and Cheyenne South Fork, both levels are not represented in Rapid, Bear Butte, and Battle Creek valleys. Table 1 lists the terraces present in each valley and their possible correlation.

This correlation is based primarily on the number and the topographic expression of terraces within the foothill belt. Two terraces are present within this belt in all the creeks studied. The lower terrace (Sturgis) rises abruptly from the present-day flood plain, and the upper terrace (Rapid) rises abruptly from the lower terrace. Thus a correlation of these two sets of terraces from one valley to

another is believed to be valid. The fact that these two sets of terraces are not at the same elevation in each valley does not invalidate the correlation. Because the creeks under consideration at one time flowed eastward, independently, across western South Dakota (prior to capture by the Cheyenne South Fork), the factors influencing rate of downcutting may well have varied in the different creeks.

The correlation of terraces below the Sturgis terrace is based on the assumption that the Bear Butte terrace was once present in Rapid Creek Valley but has since been completely removed in the planation accompanying the Farmingdale cycle. This event is quite possible, since the Bear Butte terrace is almost completely missing in the upper half of the smaller Bear Butte Creek Valley. It follows logically that the larger stream of Rapid Creek would be capable of completely removing the Bear Butte terrace.

The Farmingdale cycle of erosion is represented in Battle Creek by the present-day flood plain upstream from the Battle Creek knickpoint. Downstream from this point the Farmingdale terrace has been completely removed by stream side-cutting of the present cycle.

Knickpoints on the profiles of these streams indicate that rejuvenation in the present erosion cycle is proceeding upstream toward the Hills. Active downcutting is taking place only in the downstream sections near the Belle Fourche and Cheyenne South Fork rivers. Because the latest rejuvenation is expressed by terracing of the Farmingdale surface in both major and minor streams of the area, it follows that this rejuvenation must be related to a wave of rejuvenation which has proceeded up the Cheyenne River but which has not yet reached the headwaters of its tributaries. A direct connection is therefore established between terrace cycles in the Missouri and Cheyenne River valleys. Todd (1923, pp. 491–493) has shown that the Missouri Valley terraces are genetically related to the Wisconsin stage of continental glaciation. Presence of the Wisconsin ice sheet in eastern South Dakota resulted in ponding of the Missouri River waters along its western border. Retreat of the ice permitted the Missouri River to reexcavate its valley, leaving behind terraces which mark the glacial stages. Fillman (1929, p. 44) states: "The possibility presents itself that the valley terraces of the Black Hills region are genetically related with the glacial terraces farther east and downstream." The presence of the knickpoints in the Black Hills streams makes this possibility much more probable. It is highly probable that the Farmingdale terrace is correlative with the last glacial stage in eastern South Dakota. The inference is strong that all the Pleistocene terraces in this area (Rapid, Sturgis, Bear Butte, and Farmingdale) may owe their origin to downstream blocking by Pleistocene ice sheets.

MacClintock (1936, pp. 346–360) suggests that differential uplift has occurred in the region since late Wisconsin time. As proof he cites the existence of varved sediments in the White River Valley. He believes that these sediments, which are found at several places from the White River headwaters to the Missouri River, were deposited in an ice-dammed lake resulting from a late Wisconsin glacial invasion. He discounts the idea that the varves could have been deposited in local lakes, and thus he postulates a rise of the western part of the basin with respect to the eastern part of 2,000 feet in post-Wisconsin time. A differential uplift of this type should be reflected in the Black

Hills region by renewed downcutting of the streams in their headward portions. However, this is not the case; post-Wisconsin downcutting in those streams is limited to the sections below the knickpoints. Therefore, post-Wisconsin uplift is not indicated in the Black Hills region.

DRAINAGE PATTERNS

Most streams flowing eastward from the Black Hills are characterized by asymmetrical north-south profiles. The north-facing slopes of the valleys are steeper than the south-facing slopes.

Where asymmetry is greatest, the valleys are characterized by stream terraces which appear only on the north sides. Thus asymmetry is here the topographic expression of the unequal lateral distribution of stream terraces. Rapid Creek Valley (fig. 2) furnishes the best illustration of this phenomenon. The Rapid and Sturgis terraces are confined almost exclusively to the north side of the valley. An asymmetrial terrace distribution of this type must result from lateral southward shifting of the stream axis. Evidence supporting this hypothesis is shown in figure 4. As pointed out previously, the anomalous terraces on the south side of Rapid Creek are best explained by the hypothesis of a southward-shifting stream axis.

Asymmetry of valleys has been ascribed to many causes. Where lateral shifting of stream axis is evidenced, the possible causes may be reduced to the effects of regional dip, earth rotation, and regional tilting.

The regional dip in this area is east. Thus the effects of regional dip must be discounted because the lateral shift in stream axes is at right angles to the regional dip.

In the northern hemisphere streams are deflected to the right by the Coriolis force, an apparent force due to the earth's rotation. Thus, in an eastward-flowing stream, the steepest side of the valley should appear on the south, which is as observed in the streams under consideration. If this force has been effective in producing asymmetry, it should operate on all streams in the area, regardless of direction of flow. This is not the case, however, in the Black Hills region. Asymmetry is here limited to those streams flowing eastward from the Hills. Therefore, the Coriolis force must be ruled out as a major cause of asymmetry in this area.

The remaining possibility is regional downward tilt to the south. Unfortunately, no independent proof is available for such tilting, aside from the apparent southward shift of stream axes.

A corollary phenomenon of the asymmetrical valleys is the parallelism of tributary gulleys on the north sides of the valleys. As shown by the terrace outlines in Rapid Creek Valley (fig. 2) and Bear Butte Creek Valley (fig. 5), these gulleys trend north-northwest–south-southeast. A parallel stream pattern is usually controlled by structure, but this explanation does not apply here, as the formations are essentially flat-lying over the area.

W. L. Russell (1929, pp. 249–255) discussed the marked northwest-southeast alignment of valleys and ridges in the northwestern Great Plains. He found that this phenomenon was present in the minor drainage only. His explanation is that northwest-southeast aligned sand ridges were developed on a Tertiary surface by means of prevailing northwest winds and that the drainage pattern which originated in this way has so continued, although most of the Tertiary cover is now removed from most areas. Russell contends that this phenomenon cannot be due to tilting, for otherwise the

main streams would have shown the effects.

However, the asymmetry of the Black Hills valleys is best explained on the basis of regional tilt to the south, which probably took place after the main drainage lines of the present were established. On this basis parallel tributary gulleys are to be expected. It is postulated that, as the axes of the streams migrated southward, the tributary gulleys were lengthened by footward extension. This process would result in parallel extension of the minor drainage.

In summation, the channels of streams flowing eastward from the Black Hills have shifted southward, the migration probably starting in early Pleistocene time. The proof of this migration is found in the asymmetrical terrace distributions of the valleys and in certain anomalous terraces in Rapid Creek Valley. On the available evidence, regional downward tilt to the south is indicated.

SEDIMENTOLOGY

FIELD WORK

The field investigation involved the collection of samples for sedimentary analysis and the mapping of stream terraces. The latter problem was discussed in the physiographic section. The mapping of terraces was necessary for accurate sampling of the sediments. It was desirable to sample gravel from one terrace which could be easily traced over the area of study. The Sturgis terrace was selected for sampling. It is widespread along Bear Butte, Rapid, and Battle creeks and can be traced eastward from the Hills to the Belle Fourche and Cheyenne rivers.

Three types of samples were collected: (1) channel samples, (2) limestone pebble sets, and (3) spot sand samples.

Channel samples, weighing 150–200 pounds, were collected for mechanical and lithologic analysis. The sample portions greater than 2 mm. were hand-sieved and weighed in the field. The portions below 2 mm. were quartered for laboratory analysis, and the 16–32 mm. grades were saved for lithology counts.

Sets of Minnekahta (Permian) limestone pebbles were collected at most channel-sample localities and at additional localities for roundness and sphericity analysis. Fifty to one hundred pebbles of sizes 16–32 mm. and 32–64 mm. were collected at random from the exposures. The sphericity of each pebble was measured with an intercept gauge which measures three mutually perpendicular axes. As shown by Krumbein (1941*a*, pp. 64–72), ratios of these lengths may be used to compute the sphericity. Roundness was estimated visually by comparison with a standard set of pebble images of known roundness and sphericity.

A series of spot sand samples was collected from the present-day channel deposits of Battle Creek and the Cheyenne River. Samples of about 100 gm. (1–2 mm.) were taken from sand bars or banks.

GRAVEL ANALYSIS

PROBLEMS OF SAMPLING

Sample types.—The choice of a sample type appropriate for mechanical analysis was limited by the nature of the deposits and their exposures. Over large areas the Sturgis gravels are cemented in varying degrees with calcium carbonate. Because of this consolidation it was impracticable from the standpoint of time and labor to take samples from locations other than gravel pits, road cuts, or steep terrace scarps cut by the present-day streams.

The channel samples collected in this

study reveal the average characteristics of the gravel deposits. It was impossible to deal with one sedimentation unit, which is defined as that thickness of sediment which was deposited under essentially constant physical conditions (Otto, 1938, pp. 569–582). Insufficient exposures were available to trace such a unit, and at some sample locations not all the gravel deposit was exposed.

In Rapid Creek an approach to the sedimentation unit was realized, because most of the exposures in the Sturgis terrace revealed rather homogeneous gravel (table 2). The Sturgis gravels of Bear Butte Creek are homogeneous or poorly bedded (table 3), whereas the gravels of Battle Creek are poorly to moderately bedded (table 4). Exposures of the Farmingdale terrace are moderately to well bedded (pl. 1).

Sampling from a river terrace avoids one of the main difficulties of sampling the sediment of a present-day stream. In the latter the size of the material varies widely, depending on its location with regard to the main channel. On the other hand, a terrace deposit contains material which was deposited under varying conditions and over a wide range of time. Thus a channel sample through a terrace gives data on the average size of the load deposited by the stream at that point.

TABLE 2

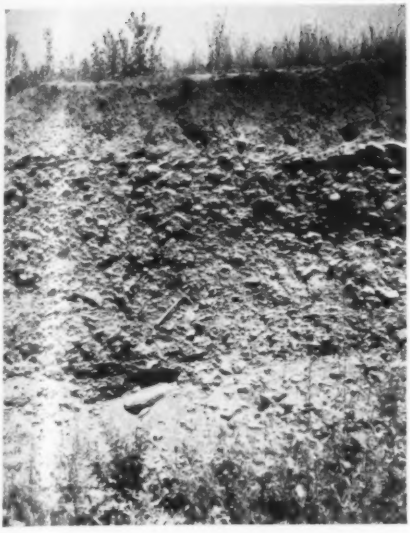
CHANNEL-SAMPLE DESCRIPTIONS, RAPID CREEK

Sample No.	Terrace	Thickness of Gravel Cap (Feet)	Length of Channel Sample (Feet)	Cementation	Bedding	Nature of Exposure
R-1	Sturgis	11	8	Medium	Homogeneous	Gravel pit
R-2	Sturgis	25	5 near base; 3 at middle	Medium	Homogeneous	Terrace rim
R-3	Sturgis	30	7 near top	Heavy	Poorly bedded; some 6-inch sand lenses	Railroad cut
R-4	Sturgis	12	6 near top	Medium	Homogeneous	Road cut
R-5	Sturgis	20	3, 3-foot channels, top to bottom	Light	Homogeneous	Road cut
R-6	Sturgis	11	3, 2-foot channels, top to bottom	Light	Poorly bedded	Gravel pit
R-7	Farmingdale	6	6	None	Moderately bedded	Road cut
R-8	Farmingdale	25+	7 near top	None	Well bedded	Road cut
R-9	Sturgis	2	2	Light	Homogeneous	Terrace rim
R-10	Farmingdale	12	8	None	Poorly bedded	Road cut

Sampling errors.—Sampling errors fall into two categories: those due to the size of the sample and those due to local variations in the deposit.

The size of the sample for mechanical

PLATE 1



A

B

C

D

PLEISTOCENE AND RECENT GRAVEL DEPOSITS

A, Sturgis terrace gravel, sample R-3, Rapid Creek; *B*, Farmingdale terrace gravel, sample R-9, Rapid Creek; *C*, flood plain gravel, sample BB-1, Bear Butte Creek; *D*, Sturgis terrace gravel, sample R-1, Rapid Creek.

analysis varied between 150 and 200 pounds, depending on the coarseness of the material. Wentworth's empirical rule was followed (Wentworth, 1926), which requires that a sample be large enough that several fragments of the largest grade are included. From probability considerations, this number of fragments should be at least four. It was not possible to include the largest boulders in the size-frequency distributions. To represent them correctly (>128 mm.) would require a sample of several hundred pounds. However, because of their relative scarcity, it is assumed that the mean size of such a large sample would

TABLE 3

CHANNEL-SAMPLE DESCRIPTIONS, BEAR BUTTE CREEK

Sample No.	Terrace	Thickness of Gravel Cap (Feet)	Length of Channel Sample (Feet)	Cementation	Bedding	Nature of Exposure
BB-1	Present-day flood plain	20+	6	None	Poorly bedded	Gravel pit
BB-2	Bear Butte	10	8	Heavy	Poorly bedded	House excavation
BB-3	Sturgis	8	5	Light	Homogeneous	Road cut
BB-4	Sturgis	10+	6	Light	Poorly bedded	Gravel pit
BB-5	Sturgis	8	5	Medium	Poorly bedded	Gravel pit
BB-6	Sturgis	8	2, 3-foot channels	Heavy	Moderately bedded	Gravel pit
BB-7	Bear Butte	11	8	None	Well bedded	Terrace rim

TABLE 4

CHANNEL-SAMPLE DESCRIPTIONS, BATTLE CREEK

Sample No.	Terrace	Thickness of Gravel Cap (Feet)	Length of Channel Sample (Feet)	Cementation	Bedding	Nature of Exposure
B-1	Sturgis	34+	10 near top; 4 near bottom	Light	Poorly bedded	Gravel pit
B-2	Sturgis	12	5, 1–2-foot channels top to base	Light	Poorly bedded	Road cut
B-3	Sturgis	20	4, 3-foot channels top to base	Light	Poorly bedded	Terrace rim
B-4	Sturgis	20	4, 3-foot channels top to base	None	Moderately bedded	Terrace rim
B-5	Sturgis	8	8	None	Moderately bedded	Terrace rim
B-6	Sturgis	12	5, 2-foot channels	None	Moderately bedded	Terrace rim

differ little from that of a smaller sample (150–200 pounds) which did not include them. This assumption is supported by Krumbein's work on the flood deposits of Arroyo Seco (Krumbein, 1942, pp. 1355–1402).

To determine what effect local variation had on the median size, the probable error was computed for the deposits at sample site R-3 of Rapid Creek. The probable error measures the chance deviation of a given sample from the average value of the material being sampled. Three 6-foot channel samples, averaging 165 pounds each, were collected from the exposure. The channels were separated horizontally by 20 feet. Standard procedures for computing the probable error were used (Krumbein, 1934, pp. 204–214). The probable error of the median size was found to be less than 2 per cent. The validity of this small sampling error may be challenged statistically because this method of error determination holds strictly only for normal distributions. The Sturgis gravel deposits do not yield normal size-frequency curves but highly skewed distributions. However, it can at least be concluded that the sampling errors due to chance deviations are small.

The standard error of the mean was used to compute sampling errors of shape and roundness. It is defined as that error which will not be exceeded in 67 cases out of 100. The mean roundness computed from 50 pebbles had a standard error of less than 1 per cent. The mean sphericity had a standard error of less than 2 per cent. The standard errors of mean roundness and sphericity of quartz sand grains were about the same as those for pebbles.

By comparing these errors with the tabulated values of size, shape, and roundness, it is seen that the errors in sampling are small enough that no significant trends of these parameters with distance will be obscured.

ANALYSIS AND PRESENTATION OF DATA

Size.—In the laboratory the quartered samples (< 2 mm.) were analyzed into Udden grades to complete the frequency distributions. The size-frequency distributions contain material in twelve size grades, from 128 mm. to $< \frac{1}{16}$ mm. (tables 5, 6, and 7).

The data show that two modes are present in most of the frequency distributions. The principal mode is in the largest sizes. A weak secondary mode appears in the sizes $\frac{1}{4}$–2 mm. In Rapid and Bear Butte creeks the secondary modes occur mainly in the $\frac{1}{4}$–1-mm. grades. In Battle Creek the secondary modes are primarily in the 1–2-mm. grades.

It was suggested by Udden (1914, pp. 736–737) that bimodal size-frequency distributions may represent a combination of traction and suspension loads. In the San Gabriel flood gravels, Krumbein (1940, pp. 639–676) found that most of the exposures contained pebbles completely surrounded by sand. Therefore, he thought it unlikely that the material represented two periods of deposition, such as openwork gravel with later infiltration of sand, and he concluded that an abrupt velocity decrease resulted in simultaneous deposition of both traction and suspension loads.

On the other hand, Fraser (1935, pp. 910–1010) contends that simultaneous deposition of large pebbles and fine sand is improbable, since the velocity of a stream carrying pebbles 10 inches in diameter would have to be decreased 60 per cent before 1-mm. size sand could be deposited. He considers it unlikely that such violent changes in current velocity always occur when coarse material is deposited. He concludes, therefore, that at

TABLE 5

SIZE COMPOSITION OF STURGIS TERRACE DEPOSITS, RAPID CREEK
(Expressed as Weight Percentages)

SAMPLE NO.	GRADE LIMITS IN MM.											
	128–64	64–32	32–16	16–8	8–4	4–2	2–1	1–½	½–¼	¼–⅛	⅛–1/16	<1/16
R-1	25.9	31.1	18.2	10.0	4.5	2.2	1.4	1.6	2.3	1.2	0.7	0.9
R-2	27.0	25.5	14.7	8.6	5.7	3.9	2.8	3.7	3.9	1.9	1.0	1.3
R-3	24.9	28.5	17.2	8.6	5.1	3.1	2.9	4.2	3.5	0.8	0.5	0.7
R-4	21.4	33.1	14.6	7.8	5.0	3.6	3.4	5.0	3.9	1.1	0.6	0.5
R-5	14.2	18.2	18.3	14.5	8.8	5.3	3.8	5.5	6.0	2.5	1.6	1.3
R-6	17.6	15.7	19.8	12.3	8.5	6.5	5.3	6.2	5.2	1.7	0.7	0.5
R-7*	7.3	20.6	21.4	15.1	9.2	6.3	4.6	6.0	6.9	1.5	0.6	0.5
R-8*	5.6	18.6	19.8	16.0	11.7	7.3	4.5	5.1	6.2	3.2	1.3	0.7
R-9	11.6	18.3	17.3	9.4	8.5	7.6	6.6	6.2	6.9	4.9	1.8	0.9
R-10*	.....	11.7	21.8	19.1	11.6	6.4	4.7	9.0	10.2	3.3	1.4	0.8

* Farmingdale terrace.

TABLE 6

SIZE COMPOSITION OF STURGIS TERRACE DEPOSITS, BEAR BUTTE CREEK
(Expressed as Weight Percentages)

SAMPLE NO.	GRADE LIMITS IN MM.												
	256–128	128–64	64–32	32–16	16–8	8–4	4–2	2–1	1–½	½–¼	¼–⅛	⅛–1/16	<1/16
BB-1*	33.8	29.2	14.9	6.9	3.6	2.4	1.9	2.0	2.0	1.6	1.0	0.5	0.2
BB-2	.....	25.5	29.4	18.1	10.1	6.1	3.2	1.7	1.6	1.5	0.9	0.9	1.0
BB-3	.....	16.1	21.7	19.8	11.6	6.7	4.6	3.9	5.0	5.4	2.8	1.4	1.0
BB-4	.....	9.8	21.8	20.2	14.1	8.6	6.5	5.8	5.9	3.6	1.8	1.2	0.7
BB-5	.....	14.5	26.3	22.6	13.2	8.3	4.4	2.2	2.7	3.0	1.3	0.9	0.6
BB-6	.....	6.0	12.0	17.3	11.8	9.1	9.1	13.6	14.8	4.2	1.2	0.6	0.3
BB-7†	.....	7.1	14.1	20.2	17.1	11.0	7.7	5.8	6.0	5.9	3.0	1.4	0.7

* Present-day stream gravel.

† Bear Butte terrace.

TABLE 7

SIZE COMPOSITION OF STURGIS TERRACE DEPOSITS, BATTLE CREEK
(Expressed as Weight Percentages)

SAMPLE NO.	GRADE LIMITS IN MM.												
	256–128	128–64	64–32	32–16	16–8	8–4	4–2	2–1	1–½	½–¼	¼–⅛	⅛–1/16	<1/16
B-1	28.3	25.4	11.5	7.5	5.9	4.4	4.5	4.7	3.5	2.3	1.1	0.6	0.3
B-2	.....	26.4	21.5	14.2	7.1	5.6	5.2	5.4	6.0	4.5	1.9	1.4	0.8
B-3	.....	12.0	14.9	12.1	10.6	10.4	10.9	12.2	8.9	4.4	1.8	1.1	0.7
B-4	.....	9.5	10.6	13.8	12.6	10.8	10.5	10.5	8.7	7.8	3.3	1.3	0.6
B-5	.....	7.2	9.2	16.6	18.6	14.3	11.7	8.9	6.4	3.0	1.4	1.5	1.2
B-6	.....	7.9	9.8	14.9	15.7	8.6	9.6	12.2	11.0	5.7	2.4	1.3	0.9

any given instant a river usually deposits only a very limited size range of material and that the finer sizes present in gravels are the result of later infiltration. He points out that the time of infiltration is a function of the current velocity and that, if the velocity fluctuates widely, the infilling of smaller sizes may follow closely after the deposition of the coarse material.

It is believed by the writer that the major portion of the fine sizes could not have been added to the deposit until the current velocity had decreased beyond their critical velocities for motion. Thus infiltration of successively smaller particles would rapidly follow deposition of the larger particles. By means of the Black Hills data one can determine whether or not the amount of material found in the secondary modes is of the right order of magnitude to represent infiltration of sand into gravel interstices.

The subject of porosity as related to systematic packing of spheres has been discussed by Graton and Fraser (1935, pp. 785–909). They found that, with systematic packing of equal-sized spheres, the loosest packing had a porosity of 47.64 per cent and the tightest packing a porosity of 25.95 per cent. If one assumes a mixture of two sizes of spherical particles having the same density—the large size making up the matrix and packed systematically and a much smaller size packed systematically within the interstices of the large size—then one can calculate the weight percentage per unit volume of each size fraction. For example, Case 1 of Graton and Fraser is selected. The unit cell of this cubic packing contains 8 spheres of radius R. The volume of the unit cell is $8.00R^3$, the volume of the unit void is $3.81R^3$, and the porosity is 47.64 per cent. Consider the unit void to be packed with small spheres of density equal to that of the large spheres and assume that the small spheres also have a cubic packing. If the size of the large spheres is very large compared to the size of the small spheres, then haphazard packing near the walls of the "container" will be relatively unimportant. Then 53 per cent of the unit volume will be occupied by large spheres. Of the remaining 47 per cent, 53 per cent will be occupied by small spheres and 47 per cent will be void. Thus only 25 per cent (i.e., 53 per cent *times* 47 per cent) of the unit volume will be occupied by small spheres. Since the densities of the spheres are assumed to be equal, then

$$\text{Weight ratio} = \frac{\text{Per cent small spheres}}{\text{Per cent small spheres} + \text{per cent large spheres}} = \frac{0.25}{0.25 + 0.53} = 32 \text{ per cent}.$$

Thus for the loosest type of systematic packing the small spheres constitute 32 per cent by weight of the total weight of the mixture.

For the tightest systematic packing of spheres (Case 6: Rhombohedral), an analogous calculation yields a weight ratio of 22 per cent.

It is obvious that the simplified conditions of the above analysis cannot be applied directly to a natural gravel. In a natural gravel there exists an almost infinite number of sizes, the particles are not spheres, the densities are different, and the packing may vary from systematic to chaotic. In spite of these complexities, an interesting comparison can be made of the theoretical and actual situations.

If one considers the median size as representing an average matrix size and the secondary mode as representing material infiltrated into the matrix, the agreement between theoretical and actual weight percentages is remarkably close. In the natural gravels the fraction assumed as matrix-void filler includes material from the "low" class to the finest-size class (i.e., Rapid Creek, sample R-5: 2 mm. to $< \frac{1}{16}$ mm.; weight per cent, 20.7). The average weight percentage of analogous size classes from 16 samples in Rapid and Bear Butte creeks is 20 per cent. This weight ratio is quite comparable to the theoretical ratios of 22 and 32 per cent. A lower actual weight ratio is to be expected, since, when more than one size is involved, the porosity is generally decreased. In general, the weight ratios of the infilling fractions increase with decreasing mean size of the sediment. Although theoretically the porosity is independent of the grain size, it usually increases with decreasing grain size because of frictional and bridging effects.

In Rapid and Bear Butte creeks, thirteen samples out of sixteen have a "low" class at 1–2 mm. Although this low class may emphasize the secondary mode, it is not the primary cause of the latter. The lack of material in the 1–2 mm. class is probably due to the size character of grain aggregates and individual grains. Primary aggregates of grains, as in igneous rocks, are usually composed of grains less than 1 mm. in size. When the aggregates, which are usually larger than 2 mm., break up, only particles less than 1 mm. result.

As shown in table 7, the size composition of Battle Creek is quite unlike that of Rapid and Bear Butte creeks. The reason for this dissimilarity is twofold. First, Battle Creek and its tributaries, unlike the other creeks, drain a large area of granite. The granite generally has a coarse texture and is in part pegmatitic. Because of its coarse texture the granite furnishes abundant material to the 1–2-mm. size class, and therefore the persistent 1–2-mm. "low" class is missing in the Battle Creek size analyses. Second, the gravel deposits of Battle Creek are better bedded than are those of the other creeks. Layers of coarse sand commonly appear in the gravel exposures. Thus the size distributions of Battle Creek may represent a mixture of two types of sedimentation units, the gravel layers contributing to the coarse-size modes and the sand layers making up the secondary modes.

The size data have been analyzed statistically in terms of the moment measures M_ϕ ("phi mean"), σ_ϕ ("phi standard deviation"), and Sk_ϕ ("phi skewness") after Krumbein and Pettijohn (1938, pp. 242–252). The statistical parameters are summarized in table 8 and plotted as functions of distance in figures 9, 11, and 12.

In all cases the mean size decreases with distance from the Black Hills (fig. 9). The marked increase in the mean size from sample 4 to sample 5 in Bear Butte Creek is due to the addition of coarse gravel from the slopes of Bear Butte.

It has been shown by other investigations that in some present-day streams the mean weight of sediment decreases exponentially as a function of distance, according to Sternberg's law:

$$W = W_0 e^{-kx},$$

where W = weight at any point, W_o = initial weight, x = distance, and k = coefficient of weight reduction. The exponential nature of this function requires that the data plot as a straight line on

semilog paper, where distance is the independent variable.

Barrell (1925, pp. 279–342) attributed this exponential size decrease to abrasion. More recently, the importance of selective transport has been recognized (Krumbein, 1937, pp. 577–601). The effects of abrasion alone on size reduction have been studied in the laboratory. In tumbling-barrel studies, where the selective action is absent, Krumbein (1941*b*, pp. 482–520) and Sarmiento (1945, pp. 1–59) found that size reduction of pebbles proceeded exponentially. A similar exponential size decrease was noted by Pettijohn and Lundahl (1943, pp. 69–78) in a study of Lake Erie beach sands. In this case, where the size reduction was large compared to the distance traveled, it is probable that selective transport was the main factor.

TABLE 8

STATISTICAL PARAMETERS OF SIZE DATA

Sample No.	Phi Mean (M_ϕ)	Phi Standard Deviation (σ_ϕ)	Phi Skewness (Sk_ϕ)	Geometric Mean Diameter in Mm. (GM_ξ)
	Rapid Creek			
R-1	−4.58	2.26	0.939	23.91
R-2	−4.12	2.69	0.687	17.38
R-3	−4.31	2.42	0.625	19.83
R-4	−4.18	2.32	0.833	18.12
R-5	−3.28	2.78	0.506	9.71
R-6	−3.48	2.78	0.332	11.16
R-7	−3.23	2.49	0.431	9.38
R-8	−2.99	2.56	0.429	7.94
R-9	−2.87	2.82	0.341	7.31
R-10	−2.34	2.56	0.310	5.06
	Bear Butte Creek			
BB-1	−5.70	2.36	0.977	51.96
BB-2	−4.52	2.24	0.924	22.94
BB-3	−3.52	2.76	0.515	11.47
BB-4	−3.38	2.52	0.472	10.41
BB-5	−4.00	2.29	0.720	16.00
BB-6	−2.47	2.81	0.327	5.54
BB-7	−1.89	2.57	0.376	3.71
	Battle Creek			
B-1	−5.04	2.76	0.611	32.89
B-2	−3.80	2.83	0.499	11.06
B-3	−2.77	2.65	0.175	6.82
B-4	−2.43	2.70	0.140	5.39
B-5	−2.52	2.48	0.189	5.74
B-6	−2.41	2.64	0.103	5.31

It is evident from the graphs of M_ϕ against distance (fig. 9) that in these streams size reduction does not follow Sternberg's law. In each case the upstream portion of the curve is steeper than the downstream portion. Sternberg stated that the gradient of a graded river also follows a logarithmic curve. On this basis, Barrell (1925, pp. 279–342) concluded that both size of gravel and gradient of a single stream are related under the same general law. Shulits (1941, pp. 622–630) discussed this relation and obtained an equation of the slope of river profiles:

$$S = S_0 e^{ax},$$

where S = slope at any point, S_0 = slope at some initial point upstream, x = distance measured upstream, and a = coefficient of slope change.

The slopes of the Black Hills streams, however, do not follow this exponential law. Nevertheless, since both mean size and slope decrease downstream, it is possible to describe one as a function of the other. Therefore, in figure 10, mean size (M_ϕ) is plotted against gradient (G, table 9) as the independent variable. As a first approximation, straight lines can be drawn through these data, indicating that the relation is linear. The equation of each curve is of the form

$$M_\phi = a + bG,$$

where M_ϕ = phi mean size, G = gradient in feet per mile, a = constant, and

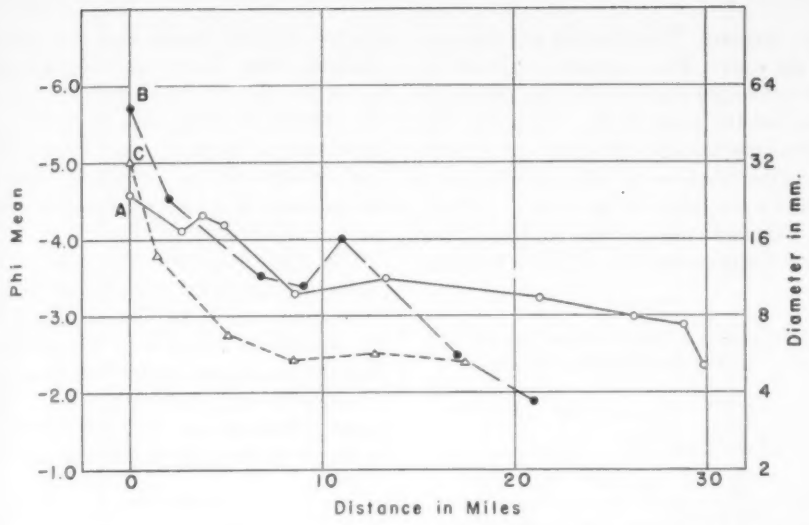


FIG. 9.—Relation of mean size to distance of transport. *A*, Rapid Creek; *B*, Bear Butte Creek; *C*, Battle Creek.

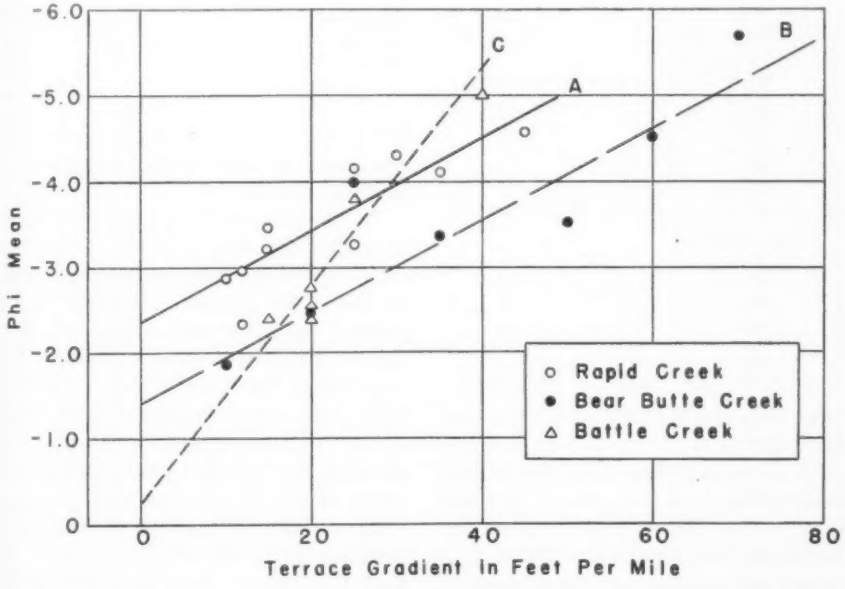


FIG. 10.—Relation of mean size to terrace gradient. *A*, Rapid Creek; B, Bear Butte Creek; *C*, Battle Creek.

b = constant. The constant b is the slope of the curve. The constant a corrects for the curve not passing through the origin and has the units of M_ϕ. The value of a is read graphically where the curve intersects the line $G = 0$. Computed values of a and b are listed in table 10.

Although the curves of Rapid and Bear Butte creeks (fig. 10) have the same slope, they are not identical. For a specific value of G the mean size of Rapid Creek gravel is greater than that of Bear Butte Creek. This is due to the fact that Rapid Creek has a greater mean discharge than has Bear Butte Creek. Thus the decrease in mean gravel size is related to three factors: (1) abrasion, (2) stream gradient, and (3) mean discharge.

It can be inferred from the observed relation between mean size and stream gradient that Sternberg's exponential law of size decrease holds only in so far as the stream gradient also decreases exponentially. Therefore, such exponential relationships can be considered only as special cases of a more general law relating size and stream gradient.

The Phi Standard Deviations (σ_ϕ) show no significant differences in the three creeks (table 8). The average σ_ϕ for all samples is about 2.6, which shows that the main part of the frequency distribution is included within 5.2 Udden grades. Thus the gravel is poorly sorted. In figure 11 the σ_ϕ is plotted against distance. The values of σ_ϕ are quite variable and show no systematic changes as a function of distance.

All the samples have a positive skewness (table 8), which means that the size distributions are asymmetrical in the direction of the largest sizes. When Sk_ϕ is plotted against distance (fig. 12), it is observed that it declines rapidly as the material is transported away from the Hills. If an originally skewed distribution at the source can be assumed, this decrease in Sk_ϕ can be explained as a combined effect of abrasion and selective transportation. It has been shown experimentally by Sarmiento (1945, pp. 1–59) that the largest sizes of material are abraded the most rapidly. Thus it could be expected that by abrasion alone, the larger particles would decrease in size

TABLE 9

TERRACE GRADIENTS OF STREAMS IN THE BLACK HILLS REGION

Sample No.	Terrace Gradient (Feet/Mile) G
Rapid Creek:	
R-1	45
R-2	35
R-3	30
R-4	25
R-5	25
R-6	15
R-7	14
R-8	12
R-9	10
R-10	12
Bear Butte Creek:	
BB-1	70
BB-2	60
BB-3	50
BB-4	35
BB-5	25
BB-6	20
BB-7	10
Battle Creek:	
B-1	40
B-2	25
B-3	20
B-4	20
B-5	20
B-6	15

TABLE 10

NUMERICAL CONSTANTS OF THE MEAN SIZE, TERRACE GRADIENT EQUATION

	a	b
Rapid Creek	−2.35	0.533
Bear Butte Creek	−1.40	0.533
Battle Creek	−0.25	1.25

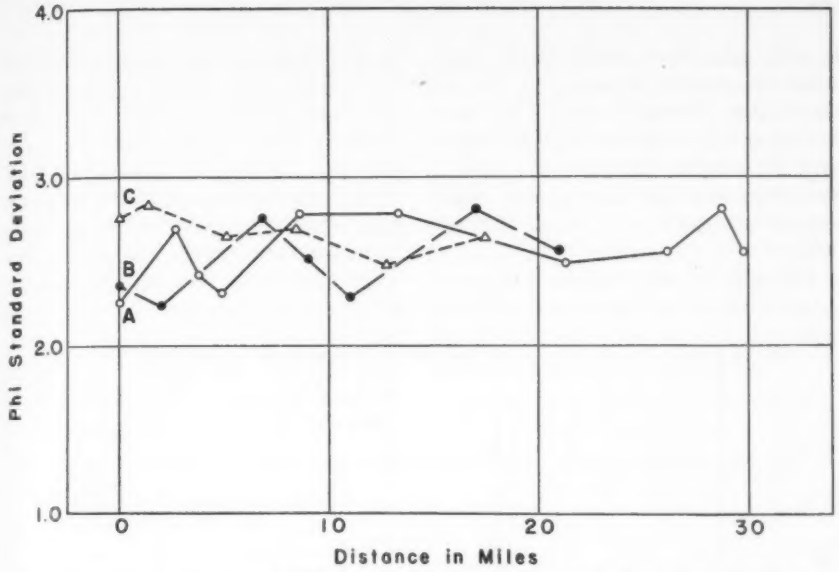


FIG. 11.—Relation of sorting to distance of transport. *A*, Rapid Creek; *B*, Bear Butte Creek; *C*, Battle Creek.

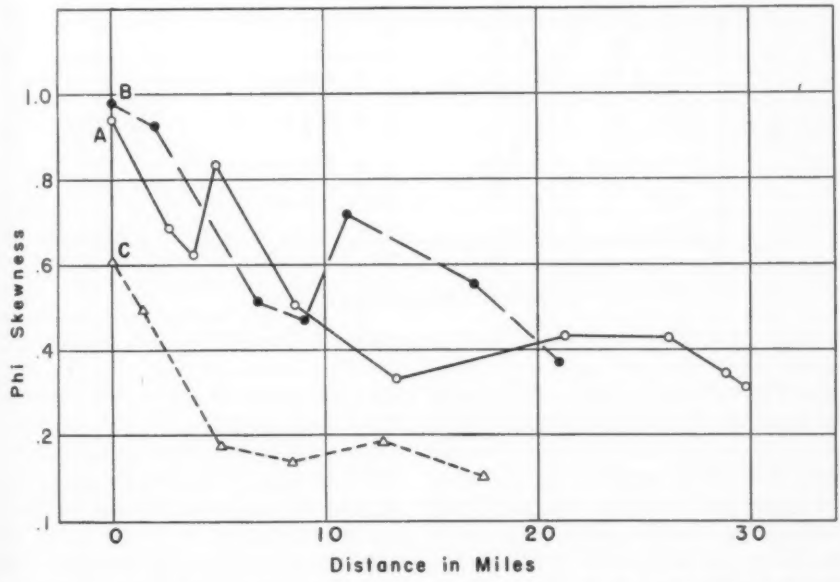


FIG. 12.—Relation of skewness to distance of transport. *A*, Rapid Creek; *B*, Bear Butte Creek; *C*, Battle Creek.

more rapidly than would smaller particles, thus tending to normalize the size distribution. Probably more important than wear is the effect of selective transport. In stream transport the smaller particles outrun the larger ones, which also works to normalize the size distribution.

Although no size distributions were obtained at the ultimate sources of the crushed material follows a geometric law in its size classes. Each size grade contains about half as much material by weight as does the next larger grade. The skewness data from the Black Hills gravel strongly suggest that the talus slopes furnishing material to the streams have such a skewed size distribution. The action of the stream in transporting this material is to reduce the skewness of

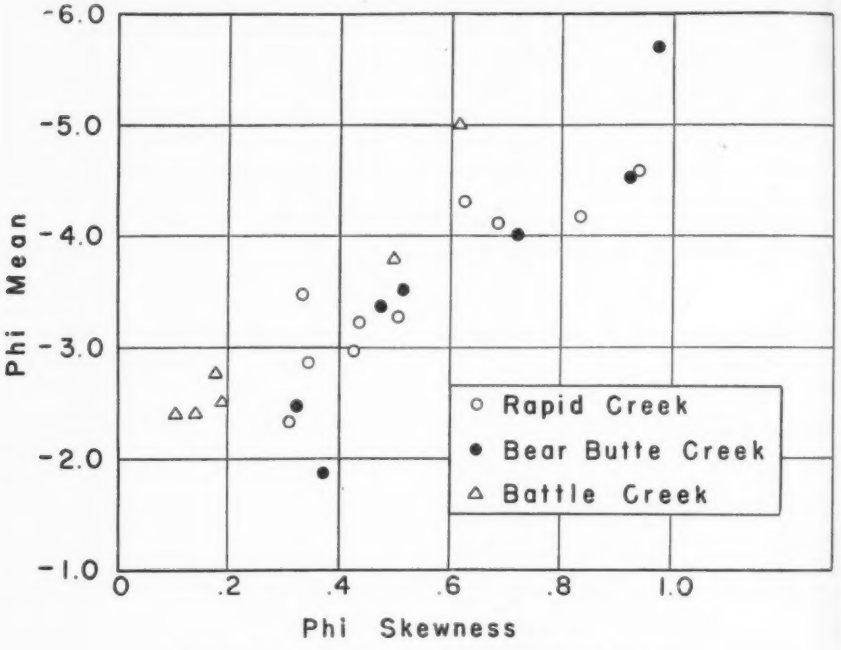


FIG. 13.—Relation of mean size and skewness (Black Hills data)

terrace gravels, some light is thrown on the problem by Krumbein and Tisdel (1940, pp. 296–305). Their experiments show that, when certain types of material (coal and quartz) are randomly crushed, the resulting size distributions are quite similar to those found in the gravel near the Black Hills. The coal and quartz broke up into fragments according to Rosin's law, which states that the distribution by differential wear and selective transport.

It is apparent from the data that skewness is a function of the mean size. In figure 13, M_ϕ is plotted against Sk_ϕ in a scatter diagram. It is seen that the samples having the largest mean size also have the most highly skewed distributions.

Additional information on the relation

of skewness to size can be obtained from a study of gravels at one location. To demonstrate this, use was made of data obtained by Kurk (1941, pp. 1–37) from Pleistocene outwash gravels at Cary, Illinois. Kurk sampled a series of sedimentation units from a vertical channel through the deposit. The writer made use of the mechanical analyses from these units to compute the phi skewness. Most of the individual sedimentation units had a bimodal size distribution. The skewness calculated from such a bimodal distribution is not representative of the skewness of either of the modes exhibited in the unit but is rather a measure of the relative importance of the two modes. If the mode in the large size is the primary one, the phi skewness will be positive.

TABLE 11

MEAN SIZE AND SKEWNESS DATA (AFTER KURK)

Phi Mean (M_ϕ)	Phi Skewness (Sk_ϕ)
−5.60	+0.84
−4.46	+0.55
−4.32	+0.93
−3.41	+0.54
−3.06	+0.57
−2.94	+0.26
−2.01	+0.34
−1.95	+0.41
−1.59	+0.05
−0.27	+0.03
+0.70	−0.18
+2.47	−0.01

The M_ϕ and Sk_ϕ values calculated for these individual sedimentation units are listed in table 11. These data are plotted as a scatter diagram in figure 14.

It is apparent that a decrease in mean size is followed by a corresponding decrease in skewness. Thus it is evident that the decrease in the skewness of the Black Hills samples with distance is a function of the decrease in mean size.

Lithology.—The size fraction (16–32 mm.) of each channel sample was analyzed for its lithologic content. The results of this analysis are given in tables 12, 13, and 14. Two hundred pebbles per sample were identified from the gravels of Bear Butte Creek, four hundred from Rapid Creek, and six hundred from Battle Creek. If we overlook the changes in lithology with distance of transport, the data reveal pronounced differences in the lithologies of the various creeks. This is a direct result of unlike source rocks in the areas which the creeks drain.

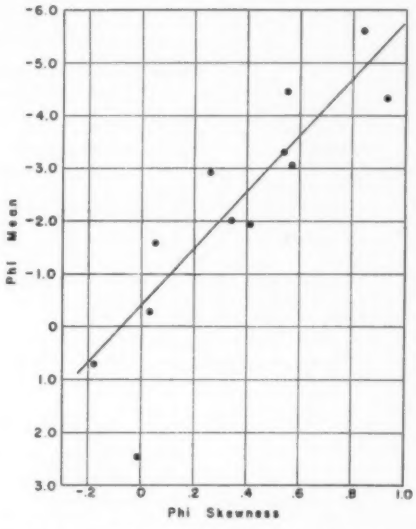


FIG. 14.—Relation of mean size and skewness. Pleistocene outwash gravel, Cary, Illinois (Kurk).

The samples nearest the Black Hills of each creek show most significant differences. In sample 1 of Bear Butte Creek, 54 per cent of the pebbles are limestone and 27 porphyry. The high percentage of limestone in this sample is due to the fact that limestone formations, which are exposed at only one place in hogbacks farther south, are repeated by anticlinal and synclinal structures in the drainage area of Bear Butte Creek. Thus more limestone is furnished to that stream.

Tertiary intrusive bodies in the northern Hills furnish the porphyry found in the gravels of Bear Butte Creek terraces.

Rapid Creek gravels are characterized by large percentages of quartzite, quartz, and pre-Cambrian metamorphic rocks (sample 1). Rapid Creek drains the central part of the Black Hills, which is predominantly composed of pre-Cambrian metamorphic rocks. Most of the quartzite tabulated here is of pre-Cambrian age.

Battle Creek drains the southern portion of the Hills. In sample 1 quartzite and quartz are conspicuous because large areas of the pre-Cambrian zone are with-

TABLE 12

BEAR BUTTE CREEK LITHOLOGY, STURGIS TERRACE
(Expressed as Number Per Cent)

	Sample Number						
	BB-1*	BB-2†	BB-3	BB-4	BB-5	BB-6	BB-7†
Pre-Cambrian metamorphics	0.5	0.5	1.0	1.5	.....	.....	0.5
Quartzite	2.5	3.0	3.5	5.0	7.0	8.0	5.0
Quartz	3.0	2.0	5.5	2.0	5.5	5.0	6.0
Porphyry and rhyolite	27.0	36.5	46.0	58.5	48.5	26.0	47.0
Limestone	54.0	38.0	16.0	22.0	23.0	30.0	18.0
Sandstone	10.5	15.5	22.0	6.5	8.5	3.0	4.5
Chert	2.5	4.5	6.0	4.5	7.5	28.5	16.0
Clay-ironstone	.....	.....	.....	.....	.....	2.0	.....
Chalcedony	.....	.....	.....	.....	.....	0.5	.....
Quartz-hematite	.....	.....	.....	.....	.....	2.0	3.0

* Present-day flood plain. † Bear Butte terrace.

TABLE 13

RAPID CREEK LITHOLOGY, STURGIS TERRACE
(Expressed as Number Per Cent)

	Sample Number									
	R-1	R-2	R-3	R-4	R-5	R-6	R-7*	R-8*	R-9	R-10*
Pre-Cambrian metamorphics	34.0	37.5	31.7	34.0	16.8	16.0	11.2	8.8	7.0	7.0
Quartzite	22.5	20.5	33.7	34.3	49.0	50.5	42.5	34.3	28.5	29.7
Quartz	14.8	16.7	8.3	15.0	22.0	18.5	28.0	25.0	21.5	24.2
Limestone	17.7	14.0	11.3	3.7	3.0	3.7	3.0	5.0	0.5	1.3
Sandstone	8.5	5.7	11.7	8.5	4.7	3.7	0.8	1.0	.....	1.3
Chert	2.5	4.3	3.3	4.5	4.5	5.3	12.7	20.5	15.8	23.5
Clay-ironstone	.....	1.3	.....	.....	.....	2.0	0.5	0.3	1.0	0.3
Concretionary limestone (from Pierre shale)	.....	.....	.....	.....	.....	0.3	0.5	3.3	10.7	7.5
Chalcedony	.....	.....	.....	.....	.....	.....	0.5	1.8	13.8	4.2
Porphyry	.....	.....	.....	.....	.....	.....	0.3	.....	.....	.....
Feldspar	.....	.....	.....	.....	.....	.....	.....	.....	1.2	1.0

* Farmingdale terrace.

in the Battle Creek drainage area. Also within this drainage area are large masses of pegmatitic Harney Peak granite. Because of the coarseness of this granite, the pebbles derived from it are either quartz or feldspar, with a few pebbles of graphic granite.

Farther out from the Hills the gravels include a few minor constituents from the Cretaceous Pierre shale and the Tertiary formations. These minor constituents are clay-ironstone, concretionary limestone, and chalcedony.

TABLE 14

BATTLE CREEK LITHOLOGY, STURGIS TERRACE
(Expressed as Number Per Cent)

	Sample Numbers					
	B-1	B-2	B-3	B-4	B-5	B-6
Pre-Cambrian metamorphics	4.0	2.7	5.7	8.8	4.0	5.2
Quartzite	22.3	17.3	23.8	34.5	38.5	42.2
Quartz	13.0	11.0	14.3	13.2	17.3	19.7
Feldspar and graphic granite	12.0	16.0	11.0	10.0	11.4	7.0
Limestone	23.3	22.2	21.0	14.0	11.3	9.0
Sandstone	23.5	28.3	20.5	11.7	10.5	6.8
Chert	1.7	2.5	3.7	7.3	6.7	9.5
Clay-ironstone	.....	.....	.....	0.5	0.3	0.3
Concretionary limestone	.....	.....	.....	.....	.....	0.3
Tourmaline	0.2	.....	.....	.....	.....	.....

To determine the effects of transportation on gravel lithology and to obtain the relative resistances of various rock types to abrasion and breakage, ratios of one rock type to another were computed. The use of a ratio rather than a direct percentage avoids the effect of an apparent decrease of one rock type, which may be due only to the addition of new material of another rock type as the stream crosses an exposure of that new material. Chert was selected as a standard of reference because it is present in all the streams and is the hardest of all rocks present. An apparent increase in the amount of chert is due, therefore, to the loss of other rocks by abrasion and breakage. By comparing other rock types to chert as a standard, the relative resistances to abrasion and breakage of the former may be calculated. These calculations are shown graphically in figures 15–17. The chert ratio is plotted against distance as the independent variable. The chert ratio is calculated as

$$\text{Chert ratio} = \frac{X}{X+Y} \cdot 100 ,$$

where X = the number of chert pebbles and Y = the number of pebbles of some other rock type. The ratio is 100 if a certain rock type does not appear in a particular sample.

In Rapid Creek (fig. 15) the ascent of all the curves shows that the proportion of chert in the terrace deposits is increasing with distance from the Hills at the expense of all other rock types. It is, as anticipated, the most resistant to abrasion and breakage. The irregularities in the curve of any one rock type are due partly to local sample variation, partly

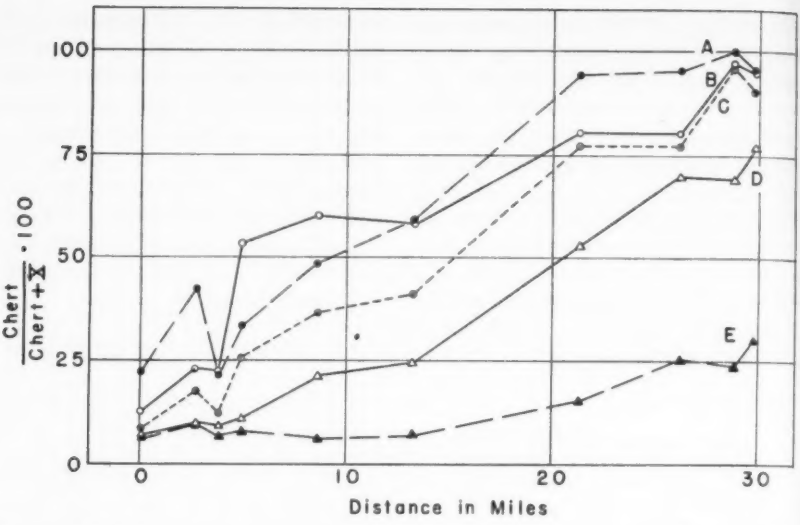


FIG. 15.—Effect of transport on rock constituents of gravel (Rapid Creek). Ratio of chert to chert plus each component: *A*, sandstone; *B*, limestone; *C*, sandstone plus limestone; *D*, pre-Cambrian metamorphics; *E*, quartz plus quartzite.

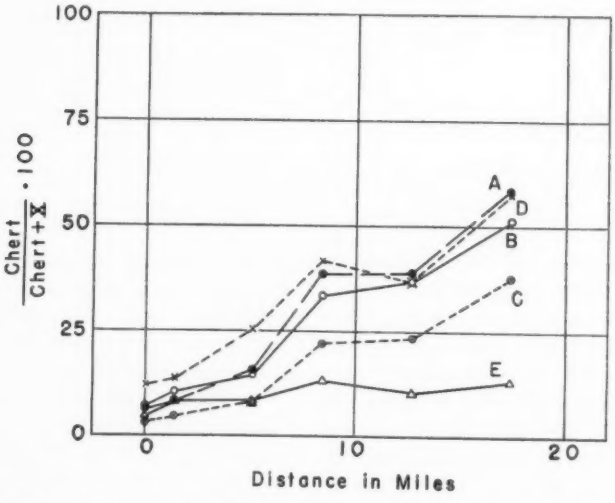


FIG. 16.—Effect of transport on rock constituents of gravel (Battle Creek). Ratio of chert to chert plus each component: *A*, sandstone; *B*, limestone; *C*, sandstone plus limestone; *D*, feldspar; *E*, quartz plus quartzite.

to influx of new material, and partly to the effects of increase or decrease of other types, which is not completely eliminated by the use of a ratio. This is illustrated by sample 3, which is from a locality about 1 mile east of the Dakota sandstone (Cretaceous) hogback. The sandstone ratio drops markedly from sample 2 to sample 3 because of the addition of sandstone to the stream from the Dakota outcrop. That the other ratios are affected by this addition is shown in the values in sample 3, where all ratios show a sympathetic decrease. East of sample locality 4, addition of limestone from the Colorado group (Cretaceous) may account for depression of the limestone curve. The sandstone curve reaches the 100 value at sample 9, indicating an absence of sandstone. This, however, does not mean that no sandstone pebbles (16–32 mm.) will be found in the gravel beyond this distance from the Hills. If a larger sample had been taken, some sandstone would undoubtedly have been found, but its percentage in the total sample would have been much reduced. It is to be expected that these curves will approach the 100 ratio asymptotically if large enough samples are taken. In general, quartz and quartzite are the most resistant to abrasion and breakage, followed by pre-Cambrian metamorphics, limestone, and sandstone. Although sandstone is composed mainly of hard quartz grains, it is the least resistant of all the rock types to abrasion and breakage, probably on account of its high friability.

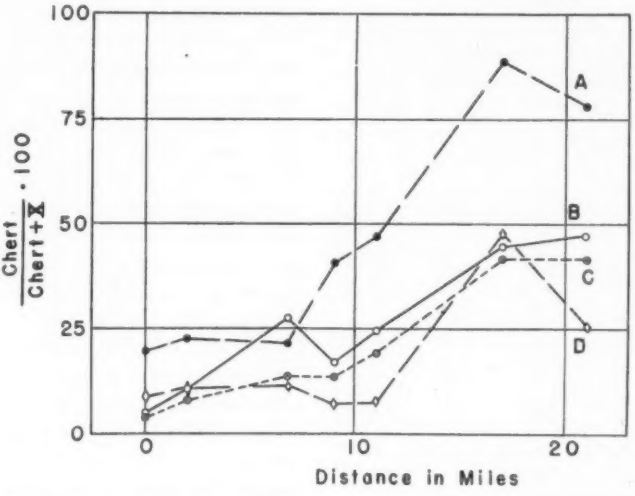


FIG. 17.—Effect of transport on rock constituents of gravel (Bear Butte Creek). Ratio of chert to chert plus each component: *A*, sandstone; *B*, limestone; *C*, sandstone plus limestone; *D*, porphyry.

The graph of Battle Creek is shown in figure 16. Sample 1 is from a locality east of the Dakota hogback, and therefore contamination from that source is absent. In general, the curves are similar to those of Rapid Creek, but the decrease in sandstone and limestone is less abrupt. This difference may be explained in two ways: Rapid Creek is a larger stream, and its gravel may have been subjected

to more vigorous transport. Moreover, the percentage of hard rock (quartzite, quartz, chert, pre-Cambrian metamorphics) in Rapid Creek is about 75 per cent near the Hills, while the same rocks in Battle Creek make up only about 40 per cent of the gravel. The limestone and sandstone pebbles of Rapid Creek are associated, therefore, with about twice as many hard-rock pebbles, which act as grinders to reduce them.

TABLE 15

STATISTICAL PARAMETERS OF SHAPE AND ROUNDNESS DATA, MINNEKAHTA LIMESTONE, RAPID CREEK

Sample No.	16–32 Mm.		32–64 Mm.	
	Mean Roundness (P)	Mean Sphericity (Ψ)	Mean Roundness (P)	Mean Sphericity (Ψ)
R-A...	0.15	0.62	0.15	0.62
R-B...	0.34	0.59	0.37	0.57
R-1....	0.39	0.51	0.49	0.56
R-C...	0.47	0.59	0.52	0.65
R-D...	0.46	0.53	0.48	0.59
R-2....	0.52	0.58	0.57	0.62
R-3....	0.55	0.62	0.59	0.65
R-6....	0.62	0.61	0.63	0.66
R-7....	0.64	0.61	.....	.....
R-E...	0.65	0.66	.....	.....
R-8....	0.65	0.64	.....	.....
R-10...	0.67	0.63	.....	.....

Feldspar and graphic granite are an important component of Battle Creek gravels. Feldspar is seen to be about as resistant as limestone. Sandstone, as found in Rapid Creek, is slightly less resistant than limestone.

The graph of Bear Butte Creek is shown in figure 17. The curves in this creek are quite erratic, owing principally to contamination by new sources of material. The Dakota hogback lies between the sources of samples 2 and 3. The sandstone curve is depressed in this zone by the addition of sandstone from the Dakota formation. The depression of the limestone curve at sample 4 is due to additions from the Greenhorn limestone (Cretaceous). Bear Butte, a Tertiary intrusive of porphyry, is located about 3 miles north of sample 3. Contributions from this body account for the depression of the porphyry curve between sample localities 3 and 5. The incongruency of the ratios in sample 7 may be due to the fact that this deposit may consist of gravels from the Belle Fourche River rather than from Bear Butte Creek.

Shape and roundness.—The effects of transportation on the shape and roundness were studied for two sizes (16–32 and 32–64 mm.) of one type of rock. The type selected had to be fairly common and easily recognized, in order to make its collection possible. It was also necessary to have a source in the area where the pebbles were angular and to have only one source to avoid obscuring the results by the addition of fresh material at any other point. The Minnekahta limestone (Permian) satisfied these requirements. It outcrops as a continuous hogback around the Black Hills, averaging 40 feet in thickness. It has a distinctive gray color tinged with pink and purple, resulting in its being called the "purple limestone." Thin shale and fine sand partings give the limestone a tabular structure.

The statistical parameters of shape and roundness obtained by the study of samples from five streams are given in tables 15–17. In figures 18–20 these parameters are plotted as functions of distance of transport. The data from Rapid and Battle Creek samples are plotted separately, whereas those of Bear Butte Creek, the Belle Fourche River, and the Cheyenne River are graphed as a continuous series. Although the Cheyenne River graph is a composite of more than one type of stream, it serves to il-

lustrate the asymptotic nature of the rounding process.

Samples from the three creeks show the same general characteristics in their roundness and sphericity curves. In Rapid and Battle Creek curves the roundness increases rapidly at first and then more slowly. The roundness curve of Bear Butte Creek samples lacks the initial sharp increase observed in the other curves. As explained in the lithology section, the Minnekahta limestone pebbles of sample 1 in Bear Butte Creek are a mixture of pebbles from two sources, one of which is rather distant, so that rather high average roundness values are observed.

TABLE 16

STATISTICAL PARAMETERS OF SHAPE AND ROUNDNESS DATA, MINNEKAHTA LIMESTONE, GRACE COOLIDGE CREEK AND BATTLE CREEK

Sample No.	16–32 Mm.	
	Mean Roundness (P)	Mean Sphericity (ψ)
C-A	0.20	0.58
C-B	0.22	0.56
C-C	0.37	0.63
C-D	0.44	0.61
B-1	0.52	0.60
B-2	0.49	0.62
B-3	0.53	0.61
B-4	0.55	0.62
B-5	0.55	0.61
B-6	0.59	0.61

The limestone pebbles of Rapid Creek reach a higher roundness value for the distance traveled from their point of origin than do those of Battle Creek. At 22.5 miles the pebbles of Rapid Creek have a mean roundness of 0.65, as compared to 0.60 at the same distance in Battle Creek. The more rapid initial increase of roundness in Rapid Creek samples accounts for this. It has been shown in the lithology section that the limestone of Rapid Creek suffered more rapid attrition by abrasion than did the limestone of Battle Creek. This observation is further supported by the more rapid rounding of Rapid Creek sediments, because rounding progresses mainly by abrasion.

TABLE 17

STATISTICAL PARAMETERS OF SHAPE AND ROUNDNESS DATA, MINNEKAHTA LIMESTONE

Sample No.	16–32 Mm.		32–64 Mm.	
	Mean Roundness (P)	Mean Sphericity (ψ)	Mean Roundness (P)	Mean Sphericity (ψ)
	Bear Butte Creek			
BB-1	0.51	0.62	0.50	0.60
BB-2	0.52	0.59	0.53	0.65
BB-3	0.55	0.66	0.55	0.61
BB-4	0.56	0.63	0.57	0.64
BB-5	0.64	0.63	0.64	0.65
BB-6	0.64	0.62	0.63	0.64
	Belle Fourche River			
BF-A	0.71	0.63	.....	.....
BF-B	0.73	0.63	.....	.....
	Cheyenne River			
Ch-A	0.68	0.65	.....	.....
Ch-B	0.70	0.67	.....	.....
Ch-C	0.70	0.60	.....	.....
Ch-D	0.73	0.62	.....	.....
Ch-E	0.72	0.64	.....	.....

Roundness is also a function of size. In the early stages the larger pebbles (32–64 mm.) are rounded at a more rapid rate than are the smaller ones (16–32 mm.). Scarcity of pebbles of large size beyond sample 6 made further comparisons impossible, but the data suggest

that the rates of rounding converge with distance. No definite conclusions can be drawn from a similar comparison of size to roundness in Bear Butte Creek.

The shape or sphericity of the Minnekahta limestone pebbles show similar characteristics in samples from all the creeks (figs. 18–20). The sphericity values fluctuate considerably in the first few miles and then remain fairly constant. The low values of sphericity encountered near the source are attributed to breakage rather than to selective transport, which would operate to increase the sphericity downstream.

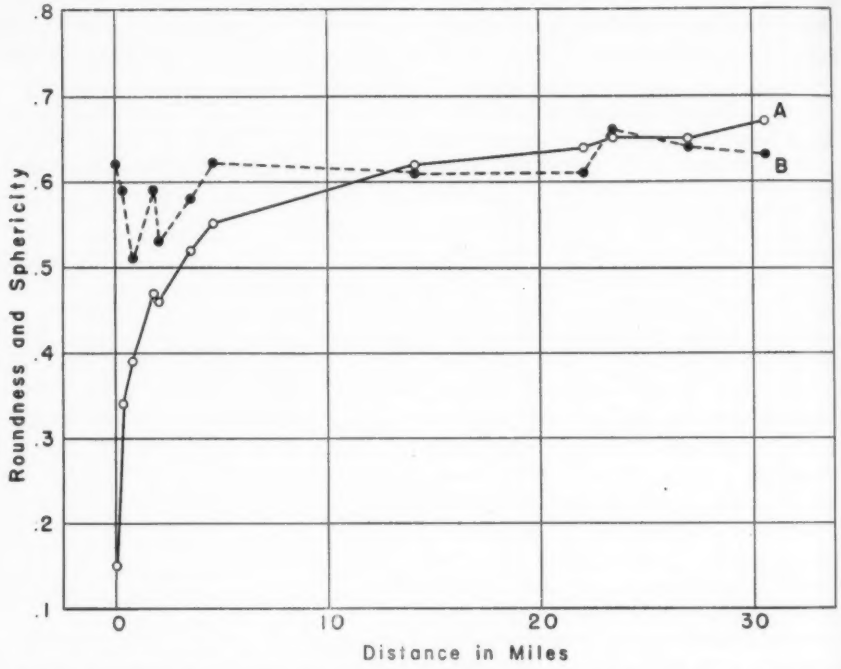


FIG. 18.—Relation of roundness and sphericity to distance of transport (Rapid Creek). Minnekahta limestone, 16–32 mm. *A*, roundness; *B*, sphericity.

One of the most important questions in a study of rounding of sedimentary particles is whether a particle, transported sufficiently far can reach a perfect roundness of 1.0 or whether some roundness value less than 1.0 is reached as a limit, depending on the composition, initial size and shape, and rigor of transport. The existing data on roundness suggest that the latter viewpoint is the correct one. Tumbling-barrel studies by Wentworth (1919, pp. 507–522) and Krumbein (1941*b*, pp. 482–520) indicate that rounding proceeds rapidly at first and then ever more slowly approaches an asymptotic value of roundness which is not exceeded. Field studies by these men support their laboratory conclusions. The present field study suggests that, in the case of limestone pebbles 16–32 mm., a limit of rounding of about 0.73–0.74 is

approached after about 200 miles of transport. The roundness data of Wadell (1935, pp. 276–277) for various sizes of the St. Peter sandstone reveal surprisingly low roundness values for a sandstone generally considered to be very well rounded. Sand on the 0.5-mm. sieve possessed an average roundness of only 0.423.

Previous investigations have shown that, although sphericity and roundness are geometrically dissimilar properties, they are both functions of grain size and thus must be functions of each other. In general, sedimentary particles of high sphericity are rounder than those of low sphericity. Russell and Taylor (1937, pp. 225–267) established this correlation

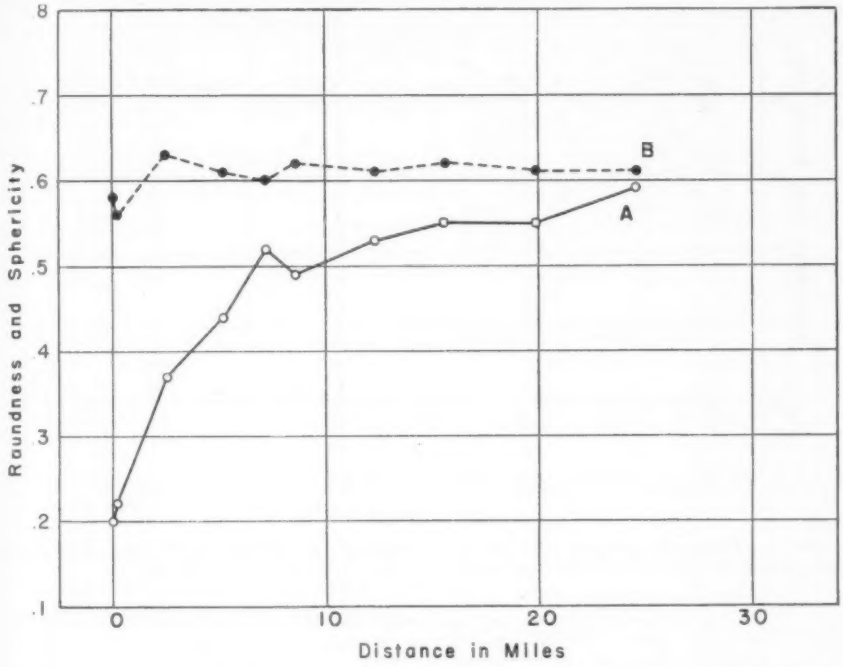


FIG. 19.—Relation of roundness and sphericity to distance of transport (Battle Creek). Minnekahta limestone, 16–32 mm. *A*, roundness; *B*, sphericity.

Reference to a limit of rounding which is not exceeded by a sedimentary particle, is, in reality, reference to the mean roundness of a sample of many particles. Individual pebbles or sand grains are commonly observed which have a roundness very close to 1.0, but the mean roundness of a sampled population of many particles is always less than 1.0. for sands of the Mississippi River, and Pettijohn and Lundahl (1943, pp. 69–78) found similar relations to exist in Lake Erie beach sands. In both these studies roundness and sphericity were found to decrease with distance of transport, but roundness decreased at a greater rate than did sphericity. Plots of sphericity against roundness from the Lake Erie

data show a linear relationship. A 4.1 per cent increase in sphericity corresponded to a 21.2 per cent increase in roundness. Although these examples illustrate the relation between roundness and sphericity, they do not provide any explanation of how that relationship was established.

In figure 21 the average roundness of Black Hills sands has been plotted against average sphericity. Although the data scatter widely, a discernible trend is apparent toward higher roundness for increasing sphericity. For an increase of 4.7 per cent in sphericity, an increase of

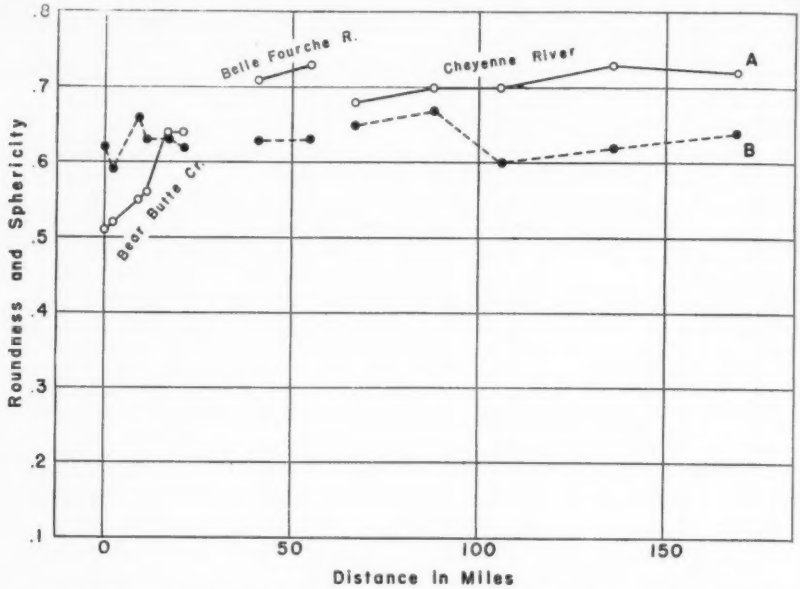


FIG. 20.—Relation of roundness and sphericity to distance of transport (Bear Butte Creek, Belle Fourche River, Cheyenne River). Minnekahta limestone, 16–32 mm. *A*, roundness; *B*, sphericity.

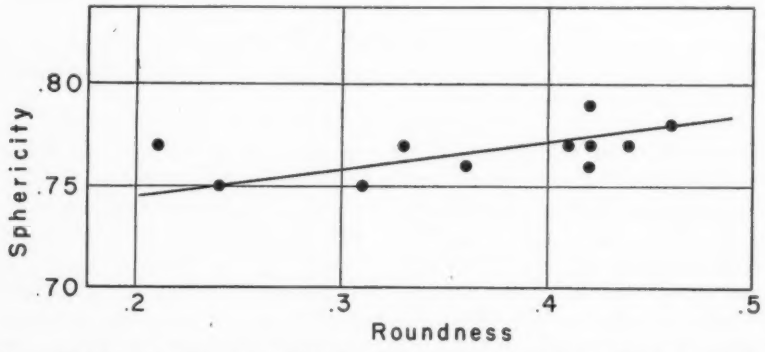


FIG. 21.—Relation of roundness and sphericity. Quartz sand, 1–1.414 mm. Arithmetic mean values of eleven samples of fifty grains each.

119.1 per cent is noted in the roundness. It is important to recognize that, although the relation of sphericity to roundness is probably basically the same in both the Lake Erie and the Black Hills sands, the actual percentage changes are not necessarily the same. Not only are the sizes studied somewhat different, but the Lake Erie samples represent a very heterogeneous mixture of sands from many sources with various histories. The decrease in their sphericity and accompanying decrease in roundness with distance of transport is apparently the result of selective transport, in which the less spherical grains in suspension outran the more spherical grains. On the other hand, the increase in sphericity and roundness of the Black Hills sands is apparently the result of abrasion. Figure 21 illustrates the much greater effect of transportation on the roundness of sand grains than on their sphericities.

Figure 22 illustrates the relation between roundness and sphericity for 16–32-mm. limestone pebbles. A 12.3 per cent increase in sphericity is accompanied by a 380 per cent increase in roundness. The ratios of sphericity increase to roundness increase are roughly the same for both the quartz sand grains and the limestone pebbles. This fact suggests that the rate of sphericity increase, as compared to the rate of roundness increase, is about the same for particles of widely different size and composition.

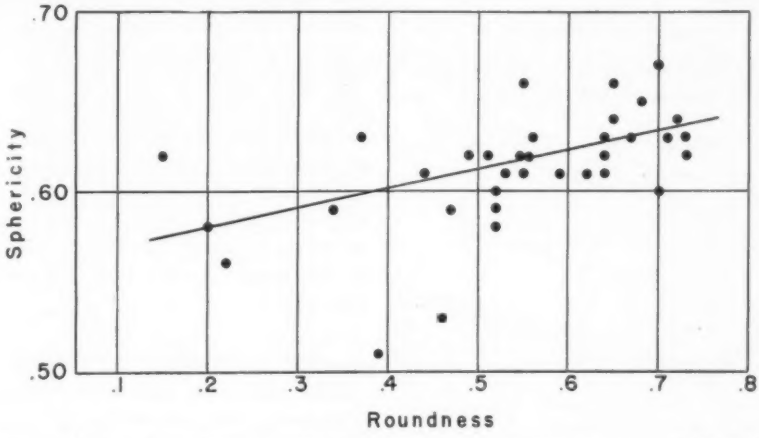


FIG. 22.—Relation of roundness and sphericity. Minnekahta limestone, 16–32 mm. Arithmetic mean values of thirty-five samples of fifty pebbles each.

SAND ANALYSIS

PROBLEMS OF SAMPLING

Sand samples from the present-day streams were collected to study the effects of transportation on small particles. The samples were limited to the 1–1.414-mm. size to eliminate contamination from outside sources, once the original source area was left behind. The source for this sand is the Harney Peak granitic area of the southern Black Hills. This area furnishes coarse arkosic sand to streams such as Battle Creek and eventually the Cheyenne River. Because of the coarseness of the sand, contamination of the samples from the finer-grained

Paleozoic and Mesozoic sandstones surrounding the Hills is negligible. This assumption is supported by Dake (1921, chap. ii) who studied the textures of a large number of sandstones. He found that in such sandstones the percentage of quartz grains in excess of 0.6 mm. was quite insignificant (0.1–0.3 per cent). Thus any textural changes in these sand samples are due to the effects of transportation.

LABORATORY METHODS

Each sand sample was quartered with an Otto microsplit (Otto, 1933, pp. 30–39). The sand was examined with a binocular microscope, and the grains unmistakably quartz were separated from the feldspar grains plus doubtful grains. The latter fraction was crushed in a mortar, grain by grain, and examined in oil with a petrographic microscope. This process was necessary because some quartz grains are impossible to distinguish from feldspar megascopically and staining techniques proved unreliable. One hundred and fifty grains were examined in this way for each sample. The probable error is estimated at 9 per cent (Krumbein and Pettijohn, 1938, p. 472).

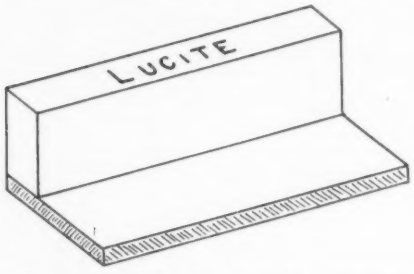


FIG. 23.—Mounting device for determining intercept sphericities of sand grains.

Shape and roundness determinations were confined to quartz grains (1–1.414 mm.) only. Fifty grains from each sample were mounted in rows on microscope slides with gum arabic and were then projected with a microprojector. The roundness was determined visually, as in the pebble analysis. The intercept method was applied to determine sphericity. A special mount was required for measurement of the short axis of the grain. This required a microscope slide and lucite block to which the slide was cemented, as pictured in figure 23. The grains are mounted in a row along one edge of the glass slide, so that their planes of maximum area are approximately parallel to the surface of the slide. The mount is then placed on a microscope stage, and the long and intermediate diameters are measured with a micrometer ocular. The slide is then turned on edge, so that it rests on the lucite block. The short diameter can then be measured directly with the micrometer ocular.

ANALYSIS AND PRESENTATION OF DATA

The statistical parameters of shape, roundness, and composition are listed in table 18. In figures 24 and 25 these data are plotted against distance as the independent variable.

Feldspar content.—The feldspar content decreases rapidly downstream in Battle Creek, a loss of 51.2 per cent in 40 miles (fig. 24). In the Cheyenne River the loss of feldspar is 13.8 per cent in 150 miles. The sand contribution of a stream such as Battle Creek must be small in comparison to the volume of sand carried by the Cheyenne River, because the higher feldspar content of the latter is apparently little affected by tributary contributions. The high feldspar content of the Cheyenne River in comparison to that of Battle Creek is a reflection of the source of the feldspar. Farther upstream on the Cheyenne River, above the mouth of Battle Creek, the tributaries are pro-

gressively shorter. They also drain areas progressively richer in feldspar. These areas are rich in pegmatites containing as much as 60 per cent feldspar. Thus these tributaries start with sand having a high feldspar content and transport it shorter distances before entering the Cheyenne River. The combination of these two factors results in the Cheyenne River's having, at any point, a higher feldspar content than does a tributary stream entering it at that point.

R. D. Russell (1937, pp. 1307–1348) took issue with the accepted idea that certain minerals, such as feldspar, are rapidly eliminated during stream transport. In the 100-mesh grade (0.147–0.208 mm.) of Mississippi River sands, he found that the feldspar content decreased 20 per cent in 1,100 miles of transport. However, on the basis of a few whole samples (all grades), the feldspar content increased slightly downstream. He concluded that destruction of feldspar by abrasion and alteration during transport is offset by other factors, such as selective sorting on the basis of size, the breakage of larger grains thus adding to the feldspar content of the smaller sizes.

Although only one size was studied in the Black Hills sands, the data suggest that wear is much more effective in reducing feldspar in streams such as Battle Creek and the Cheyenne River than it is in the Mississippi River. The decline in feldspar in the Black Hills streams can be attributed only to a combination of abrasion and weathering during transport. Contamination is absent, as is any selective sorting on the basis of size. The results are comparable to those obtained by Mackie (1896, pp. 148–172), who found that the feldspar content of certain streams in Scotland decreased as much as 50 per cent in 30–40 miles. It is concluded that in streams similar to Battle Creek and the Cheyenne River, the feldspar content of coarse sand is rapidly reduced by the effects of transportation.

Shape and roundness.—The question of how rapidly and under what conditions sand grains become rounded has long been perplexing. In a recent article Twenhofel (1945, pp. 59–71) summarized the arguments. He concluded, on the basis of the evidence at hand, that rounding of sand grains is largely, if not entirely, done in traction transport. Furthermore, he concluded that quartz grains of sand dimensions are very little, if at all, rounded in streams, especially in high-velocity streams, where the general tendency is in the direction of increasing angularity. Contrary to this view, Krynine (1940, p. 81) reported that in the initial stage of transport the passage from angular to subangular sand grains is ac-

TABLE 18

STATISTICAL PARAMETERS OF SHAPE, ROUNDNESS, AND COMPOSITION, SIZE CLASS 1–1.414 MM., BATTLE CREEK AND CHEYENNE RIVER

SAMPLE NO.	MEAN ROUNDNESS (P)	MEAN SPHERICITY (ψ)	PER CENT FELDSPAR
	Battle Creek		
SS-1	0.21	0.77	35
SS-2	0.24	0.75	29
SS-3	0.31	0.75	23
SS-4	0.33	0.77	20
SS-5	0.36	0.76	17
	Cheyenne River		
SS-6	0.42	0.76	29
SS-7	0.41	0.77	30
SS-8	0.42	0.77	27
SS-9	0.42	0.79	26
SS-10	0.46	0.78	24
SS-11	0.44	0.77	25

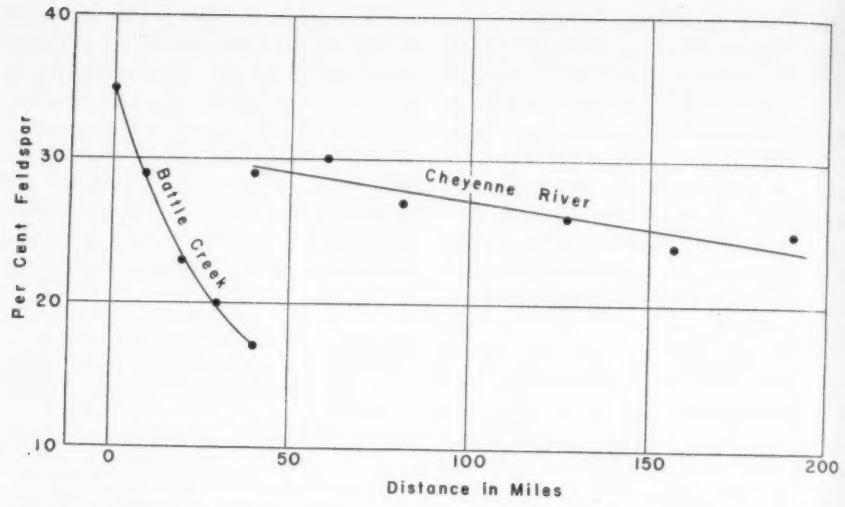


FIG. 24.—Relation of percentage of feldspar to distance of transport (Battle Creek and Cheyenne River). Size class, 1–1.414 mm.

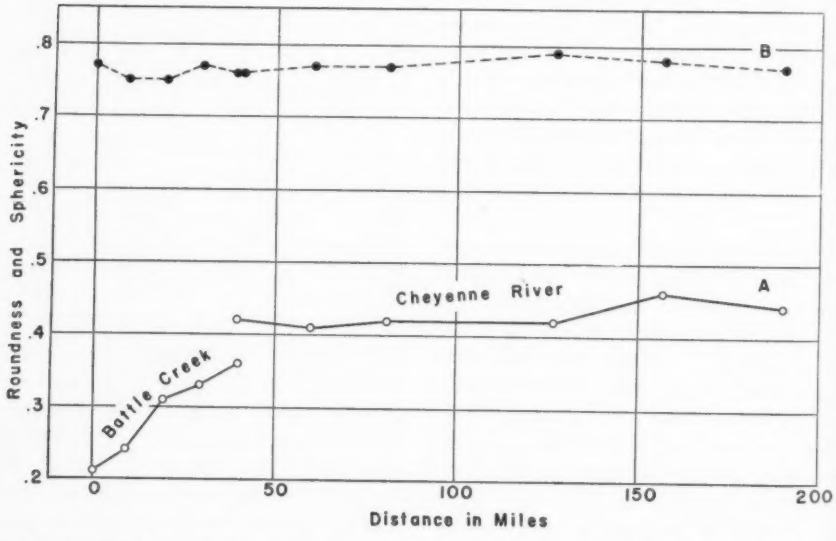


FIG. 25.—Relation of roundness and sphericity to distance of transport (Battle Creek and Cheyenne River). Quartz sand, 1–1.414 mm. *A*, roundness; *B*, sphericity.

complished in a very short period. The Battle Creek roundness curve (fig. 25) shows this to be true in quartz sand (1–1.414 mm.). The grains in the Cheyenne River show a continued but much slower increase of roundness with distance. The higher roundness values of the Cheyenne River samples reflect the greater distance of transport that the grains have experienced in that river before reaching the mouth of Battle Creek.

The change of sphericity with distance is shown in figure 25. In Battle Creek the sphericity values are too irregular for one to discern any trend. In the Cheyenne River a slight increase in sphericity with distance is noted.

These results are different from those found by Russell and Taylor (1937, pp. 225–267). They found that in 1,100 miles of transport in the Mississippi River the arithmetic mean roundness of the sizes (0.074–0.417 mm.) decreased from 0.234 to 0.179. In the same distance the sphericity decreased from 0.825 to 0.809. The decrease in roundness was attributed to breakage primarily, although selective sorting on the basis of shape would account for the same result. It is a curious paradox that breakage of sand grains should be so prevalent in the Mississippi River and apparently absent in a high-velocity stream like Battle Creek. The rounding of quartz sand grains in Battle Creek can be accounted for only by abrasion. Because only quartz grains were studied, change in mineral composition is not a factor, nor is contamination from other sand sources, since there are none in that size range. Selective sorting on the basis of shape is not a factor, inasmuch as no discernible sphericity trends are present.

For the above reasons, it is concluded that the increase in grain roundness observed in the Cheyenne River is probably due to abrasion also. It is possible that here the increase may be due to a selective sorting on the basis of shape, as the sphericity rise is about equal to the roundness increase. However, the rounding of grains in Battle Creek was seen to be completely independent of sphericity change, so it is not necessary to rely on sphericity change to explain rounding in the Cheyenne River. Abrasion alone is adequate.

EQUATION OF ROUNDING

Sedimentary particles have been observed to become rounder when transported by streams. This has been proved for particles of pebble size by many investigators. Data from Battle Creek show that streams also round sand grains as small as 1–1.414 mm. The first quantitative measure of the rate of rounding for pebbles was made by Wentworth (1919, pp. 507–522), who found that rounding proceeds rapidly at first and then less rapidly with distance. Krumbein (1940, pp. 639–676) expressed this relationship with the following differential equation:

$$\frac{dP}{dx} = k\,(P_0 - P)\,, \qquad (a)$$

which states that the rate of change of roundness (P) with distance (x) is equal to the difference between the roundness at any point and some limiting value of roundness (P_0), multiplied by a proportionality constant k. Solution of this differential equation gives:

$$P = P_0(1 - e^{-kx})\,, \qquad (b)$$

which shows the exponential nature of the relationship. This equation adequately fits the roundness data from San Gabriel Canyon.

Later tumbling-barrel experiments by Krumbein (1941*b*, pp. 482–520) showed

that the function was more complicated. Roundness plotted against distance on semilog paper did not give a straight line, as required for an exponential function of this type. Sphericity plotted as an essentially straight line, but roundness showed an initial steep curve and a curve which paralleled the sphericity curve after about 5 miles.

Krumbein developed the following differential equation to fit the roundness curve:

$$\frac{d(P-P_0)}{ds} = b(\psi-\psi_0) - a_2(P-P_0). \quad (c)$$

Solution of this equation gives:

$$P_0 - P = (P_0 - P_i)\, e^{-a_2 s} + \frac{b(\psi_0-\psi_i)}{a_2-a_3} \times [e^{-a_3 s} - e^{-a_2 s}], \quad (d)$$

where P_i = initial roundness, ψ_0 = limiting sphericity, ψ_i = initial sphericity, a_2 and a_3 = coefficients of rounding and sphericity, respectively, and b = shape coefficient in rounding.

Krumbein contended that the initial steep part of the rounding curve is controlled by the first term in equation (*d*). The long-term aspects of rounding, however, are controlled by the rate of sphericity increase, as shown by the second term in equation (*d*). Thus Krumbein found that, for certain abrasive conditions in a tumbling barrel, the long-term aspects of rounding are governed by the initial sphericity of the particle and the rate of sphericity increase.

Similar, but more extensive, experiments were later made by Sarmiento (1945, pp. 1–59). Limestone pebbles of three sizes (16, 32, and 64 mm.) were abraded in a tumbling barrel, with and without sand, each size alone and also in mixed sizes. In general, roundness increased, as found by Krumbein. However, sphericity change was very erratic. When each size was abraded separately, the sphericity behaved irregularly, either showing no change or a slight decrease. When the three sizes were abraded together, the sphericities of the 32- and 64-mm. sizes decreased slightly and that of the 16-mm. size markedly (0.69–0.48 in 20 miles). This sphericity decrease was ascribed to breakage. Sarmiento concluded that roundness changes are independent of sphericity changes.

The Black Hills field data tend to support Sarmiento's laboratory conclusion. Graphs of pebble sphericity plotted against distance (figs. 18–20) show no obvious systematic increase in sphericity. The initial sphericity irregularities have been discussed previously.

It is apparent that neither of the assumptions expressed in Krumbein's differential equations (*a*) and (*c*) is quite correct. In the following treatment it has been assumed that the rate of change of roundness with distance is not only proportional to the difference between the roundness at any point and a limiting roundness but also to some power of the distance traveled.

Expressed mathematically:

$$\frac{dP}{dS} = KS^a(P_L - P), \quad (1)$$

where P = roundness, S = distance, K = constant of proportionality, a = a negative constant, and P_L = limiting value of roundness.

To avoid confusion in symbolism, P_L is used for the limiting value of roundness instead of P_0, which in most exponential notations indicates an initial value.

To account for not starting where $P = 0$, let $S = x + x_0$, where $S = 0$ when $P = 0$. To simplify the mathematics and form of the solution, let

$K = nr$ and $a = n - 1$, where n and r are constants. Then,

$$\frac{dP}{dx} = n\,r\,(x + x_0)^{n-1}(P_L - P). \quad (2)$$

Solution of this differential equation follows:

$$\frac{dP}{P_L - P} = n\,r\,(x + x_0)^{n-1}dx\,.$$

Then, integrating, we obtain:

$$-\log_e(P_L - P) = r\,(x + x_0)^n + C\,.$$

The parameters of this equation are n and r, which can be obtained graphically by converting equation (3) to the log base 10, as follows:

$$-2.3\log_{10}\frac{P_L - P}{P_L} = r\,(x + x_0)^n.$$

Take the log of both sides, then

$$\log_{10}\left(-2.3\log_{10}\frac{P_L - P}{P_L}\right) = \log_{10} r + n\log_{10}(x + x_0). \quad (5)$$

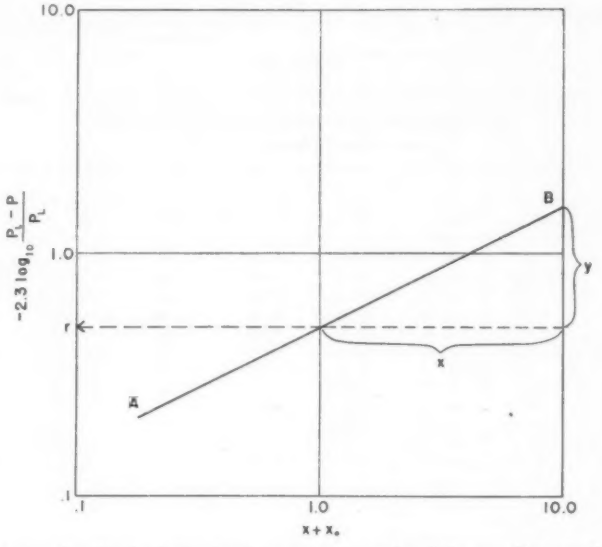


FIG. 26.—Graphical solution for the constants n and r of the rounding equation

To evaluate C, at $x + x_0 = 0$, $P = 0$. Then

$$-\log_e P_L = C\,.$$

Substitution of the value of C gives

$$\log_e\frac{P_L - P}{P_L} = -r\,(x + x_0)^n, \quad (3)$$

$$\frac{P_L - P}{P_L} = e^{-r(x+x_0)^n}.$$

The solution of the differential equation thus is:

$$P = P_L\,[1 - e^{-r(x+x_0)^n}]. \quad (4)$$

This equation is of the form $y = r + nx$, which may be plotted on logarithmic paper (fig. 26). The slope of the line AB is n and equals y/x by direct measurement. To find r, let $\log_{10}(x + x_0) = 0$. Then $r = -2.3\log_{10}(P_L - P)/P_L$ at the intersection of line AB and $x + x_0 = 1.0$.

The rounding of pebbles observed in two creeks and in one tumbling-barrel experiment has been treated on the basis of the above analysis. Calculation sheets are shown in tables 19–21.

Certain assumptions must be made with regard to the values of x_0 and P_L in each calculation. The quantity x_0 represents the theoretical distance that a pebble would have traveled to increase its roundness from zero to the value found in the outcrop. However, no transport is actually implied here, because that initial rounding may be due to weathering. For any given case, the choice of x_0 depends on the rate of initial rounding, which in the cases cited was highest for Rapid Creek and lowest for Battle Creek, with Sarmiento's experiment falling between the two. The choice of P_L considerably affects the other extreme of the curve. Choices of P_L from 0.02 to 0.05 higher than the last observed roundness value were found to be most satisfactory.

The data have been plotted on logarithmic paper in figure 27. This graph determines the parameters r, n, K, and a in table 22.

The constant r is the coefficient of rounding. However, it is not identical

TABLE 19

COMPUTATION CHART (FOR DETERMINATION OF PARAMETERS r AND n), RAPID CREEK (MINNEKAHTA LIMESTONE PEBBLES, 16–32 MM.)
($x_0 = 0.01$ Miles; $P_L = 0.72$)

Sample No.	x (Miles)	$x+x_0$ (Miles)	P	P_L-P	$(P_L-P)/P_L$	$\log_{10}(P_L-P)/P_L$	$-2.3\log_{10}(P_L-P)/P_L$
R-A	0	0.01	0.15	0.57	0.79	−0.1024	0.236
R-B	0.3	0.31	0.34	0.38	0.53	−0.2757	0.635
R-1	0.8	0.81	0.39	0.33	0.46	−0.3372	0.777
R-C	1.8	1.81	0.47	0.25	0.35	−0.4559	1.050
R-D	2.0	2.01	0.46	0.26	0.36	−0.4437	1.020
R-2	3.5	3.51	0.52	0.20	0.28	−0.5528	1.277
R-3	4.6	4.61	0.55	0.17	0.24	−0.6198	1.425
R-6	14.1	14.11	0.62	0.10	0.14	−0.8537	1.880
R-7	22.1	22.11	0.64	0.08	0.11	−0.9586	2.200
R-E	23.5	23.51	0.65	0.07	0.10	−1.0000	2.300
R-8	27.0	27.01	0.65	0.07	0.10	−1.0000	2.300
R-10	30.6	30.61	0.67	0.05	0.07	−1.1549	2.540

TABLE 20

COMPUTATION CHART (FOR DETERMINATION OF PARAMETERS r AND n), BATTLE CREEK (MINNEKAHTA LIMESTONE PEBBLES 16–32 MM.)
($x_0 = 0.5$ Miles; $P_L = 0.65$)

Sample No.	x (Miles)	$x+x_0$ (Miles)	P	P_L-P	$(P_L-P)/P_L$	$\log_{10}(P_L-P)/P_L$	$-2.3\log_{10}(P_L-P)/P_L$
C-A	0	0.5	0.20	0.45	0.69	−0.1612	0.370
C-B	0.2	0.7	0.22	0.43	0.66	−0.1805	0.415
C-C	2.1	2.6	0.37	0.28	0.43	−0.3665	0.843
C-D	4.5	5.0	0.44	0.21	0.32	−0.4949	1.14
B-1	6.5	7.0	0.52	0.13	0.20	−0.6980	1.60
B-2	7.8	8.3	0.49	0.16	0.25	−0.6021	1.39
B-3	11.4	11.9	0.53	0.12	0.18	−0.7447	1.72
B-4	14.5	15.0	0.55	0.10	0.15	−0.8239	1.89
B-5	18.5	19.0	0.55	0.10	0.15	−0.8239	1.89
B-6	22.6	23.1	0.59	0.06	0.09	−1.0458	2.41

with either k or a_2 of Krumbein's equations (a) and (b), since it is equal to K/n. Only if $n = 1$ or $a = 0$ does r equal Krumbein's k.

The use of n permits the roundness data to be plotted as a straight line on semilog paper, where the ordinate is $(P_L - P)/P_L$ and the abcissa is some power (n) of the distance $(x + x_0)$. In Rapid Creek n was found to be about $\frac{1}{3}$; in the other cases, $\frac{1}{2}$.

Thus the history of the rounding of

TABLE 21

COMPUTATION CHART (FOR DETERMINATION OF PARAMETERS r AND n)
SARMIENTO'S TUMBLING-BARREL, SECOND EXPERIMENT (LIMESTONE PEBBLES, 32 MM.)
($x_0 = 0.2$ Miles; $P_L = 0.74$)

Sample No.	x (Miles)	$x - x_0$ (Miles)	P	$P_L - P$	$(P_L - P)/P_L$	$\log_{10}(P_L - P)/P_L$	$-2.3 \log_{10}(P_L - P)/P_L$
1	0	0.2	0.21	0.53	0.72	−0.1427	0.328
2	0.17	0.39	0.22	0.52	0.70	−0.1549	0.357
3	0.33	0.53	0.27	0.47	0.64	−0.2007	0.446
4	0.50	0.70	0.31	0.43	0.58	−0.2366	0.544
5	1.0	1.2	0.36	0.38	0.51	−0.2925	0.673
6	2.0	2.2	0.46	0.28	0.38	−0.4203	0.969
7	3.0	3.2	0.49	0.25	0.34	−0.4686	1.08
8	4.0	4.2	0.50	0.24	0.32	−0.4949	1.14
9	5.0	5.2	0.56	0.18	0.24	−0.6198	1.42
10	7.0	7.2	0.59	0.15	0.20	−0.6980	1.61
11	9.0	9.2	0.60	0.14	0.19	−0.7213	1.66
12	12.0	12.2	0.64	0.10	0.135	−0.8697	2.00
13	16.0	16.2	0.67	0.07	0.095	−1.0223	2.35
14	20.0	20.2	0.70	0.04	0.054	−1.2677	2.92
15	30.0	30.2	0.71	0.03	0.040	−1.3970	3.21
16	40.0	40.2	0.72	0.02	0.027	−1.5870	3.65

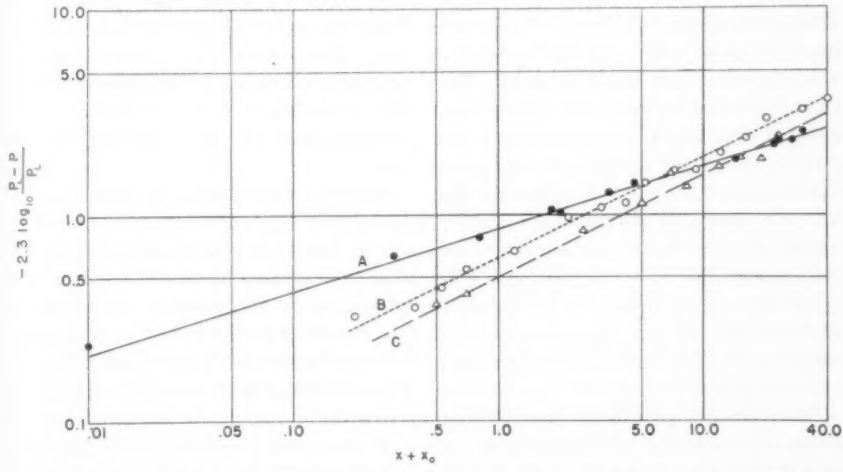


FIG. 27.—Logarithmic plot of rounding equation data. *A*, Rapid Creek; *B*, Sarmiento's second experiment; *C*, Battle Creek.

particles in a stream can be expressed by two parameters and by an equation, which, in the apparent absence of any sphericity effect, more correctly expresses the factors involved.

GEOLOGICAL INFERENCES

ABRASION AND SELECTIVE TRANSPORT

As previously stated, size reduction in a stream may be effected by two processes: (1) selective transport and (2) abrasion and breakage. Hitherto it has been impossible to evaluate these two processes quantitatively.

TABLE 22

NUMERICAL CONSTANTS OF THE ROUNDING EQUATION

	r	n	$K=nr$	$a=n-1$
Rapid Creek (16–32 mm.)	0.86	0.31	0.266	−0.69
Sarmiento 2d experiment, 32 mm.	0.62	0.50	0.310	−0.50
Battle Creek (16–32 mm.)	0.50	0.50	0.250	−0.50

The competence of a stream to carry a certain size of material is a function of stream discharge and gradient. As the gradient of a stream decreases away from its headwaters, the mean size of sediment carried is decreased. The correlation between mean size and stream gradient has been shown in figure 10. Thus the size decrease shown in the Black Hills terrace deposits must be mainly a function of selective transport. However, part of this size decrease is certainly due to abrasion and breakage. Pebbles become rounder in stream transport, which is proof that abrasion is taking place.

The lithology data (table 13) furnish a means of computing the proportion of size decrease due to abrasion. In sample R-1 (Rapid Creek) the rock types may be divided into two groups: the hard rocks (chert, quartz, quartzite) and the soft rocks (sandstone, limestone, pre-Cambrian metamorphics). The hard rocks constitute about 40 per cent of sample R-1 and the soft rocks 60 per cent. In a distance of 30 miles (sample R-10) the hard rocks constitute about 90 per cent of the sample and the soft rocks 10 per cent (recomputed to 100 per cent). Because it is unlikely that the decrease in soft rocks is due to any selective action, it must be accounted for by abrasion. The number percentages may be regarded as volume percentages. Thus in 30 miles of transport the volume of soft rocks has decreased from 60 to 10 per cent, a reduction of 50 per cent in a unit volume made up of both soft and hard rocks. A reduction of 50 per cent in a unit volume of a sphere results in a 20 per cent decrease in diameter. Therefore, on the basis of abrasion alone, one would expect a size reduction of 20 per cent in the mean diameter of the gravel in 30 miles. However, the size data from Rapid Creek reveal a decrease in that distance from about 24-mm. diameter to 5-mm. diameter, a reduction of about 80 per cent. The conclusion is that selective transport accounts for 75 per cent of the size reduction observed in Rapid Creek and abrasion for the remaining 25 per cent.

Similar calculations for Battle Creek reveal that 84 per cent of the size reduction is due to selective transport and 16 per cent to abrasion. Evidence furnished by the rates of rounding of limestone pebbles gives further proof that abrasion is less effective in Battle Creek than in Rapid Creek. Figures 18 and 19 illustrate this fact.

It has been assumed that the loss of the 16–32-mm. soft rocks by abrasion is an average loss for the entire range of

sizes. This assumption is believed to be justified by the fact that the average size of all channel samples is 12 mm., only slightly less than the size studied.

INDICES OF MATURITY

The main effort in this work has been directed toward a solution of some of the problems involved in the transportation of sedimentary material in streams. An attempt has been made not only to measure quantitatively the action of stream transport but also to define the fundamental principles which govern the measured effects.

Quantitative measurements, such as change of roundness or feldspar content of a sand with distance of transport, enable one to derive the relationships involved in such changes. Knowledge of these relationships provides a basis for extrapolating the quantitative data beyond the scope of observation and experimentation.

The importance of this possibility of extrapolation appears in consideration of what may be called "indices of maturity." Three fundamental "indices" are roundness, sphericity, and lithology. On the basis of these "indices" a clastic deposit may be classified as to its degree of maturity. At the extreme youthful end of the scale a clastic sediment is characterized by extreme angularity and relatively low sphericity of the component particles and a high percentage of chemically and mechanically unstable constituents. At the other extreme of old age a clastic sediment is composed of particles having a high roundness and high sphericity and lacking any appreciable percentage of chemically and mechanically unstable constituents.

The concept of maturity as here expressed is concerned not only with the stage of maturity reached by any sediment but also with the effectiveness of different geologic agents in producing that stage of maturity. The Black Hills data provide a means of calculating the effects of stream transport on some of these "indices of maturity."

Sand roundness.—Sand from the vicinity of Harney Peak represents material close to the youthful end of the maturity scale. It is very angular and has a high percentage of feldspar. The other end of the scale is represented by the St. Peter sandstone (Ordovician), a very pure, well-rounded quartz sand (averaging above 98.0 per cent silica). Wadell (1935, pp. 276–277) computed the roundness of several size grades of samples from this sandstone. His data have been plotted on logarithmic paper in figure 28. These data plot as a straight line and illustrate the relation between roundness and grain size. The size-roundness relation has been extrapolated to larger sizes by the writer by means of a dashed line. The extrapolation indicates that sand grains 1–1.414 mm., like those studied in the Black Hills sands, would possess a roundness of about 0.5. Thus it is indicated that the roundness of sand grains in a very mature sand is relatively low, further evidence that a limit of roundness is reached.

If a roundness value of 0.5 is assumed to be the limit of rounding for quartz grains 1–1.414 mm. in size, one can calculate the distance such a particle would have to be transported in a stream to reach this limiting value. The equation of rounding (4) developed in a preceding section was applied to the roundness-distance data of quartz sand (table 14). The constant n in this equation was found to equal 0.64 and r to equal 0.10. It was assumed that the limit of rounding is 0.5 and that the roundness at x miles is 0.499. Solution of this equation for x re-

veals that, to round a 1–1.414-mm. quartz sand grain to a roundness of 0.499, the grain would have to be transported a distance of about 600 miles. Half this rounding is accomplished in the first 20 miles. It is apparent that for very coarse quartz sand a mature index of rounding is reached in a surprisingly short distance of stream transport. On the basis of data available at present it is not possible to calculate the distance of transport required to round to their limit sands of smaller size. Wadell's data (fig. 28) reveal that the smaller sizes have correspondingly lower maturity indices of roundness. Since the process of rounding is a function of size, it is probable that sand grains less than 1 mm. would require far greater distances of transport to reach their limits of rounding. Unfortunately, Thiel's experiments on abrasion of sand grains furnished no quantitative roundness data. Experiments of that type, but which include quantitative roundness measures, should provide data for approximating the distances required to round quartz grains of small size to their limits of rounding.

Sand sphericity.—Studies do not establish sphericity as a reliable index of maturity. For it to be useful in this respect the sphericity of a youthful sand should be noticeably different than that of a mature sand. Some evidence on this question is found by comparing sphericities of quartz grains from the very youthful sands of the Black Hills with those of the mature St. Peter sandstone. The intercept sphericities of the former average about 0.76, while Wadell's data from the St. Peter sandstone for sphericities of grains of comparable size average about 0.86. Wadell's sphericities, however, are projection sphericities, which err in being too high as compared to intercept sphericities. Comparison of intercept with projection sphericities of the same samples from the data of Pettijohn and Lundahl (1943, pp. 69–78) indicates that the latter average about 0.07 too high. Thus it is indicated that the sphericity index of a youthful sand is too close to that of a mature sand to be of any practical value. Corroborative evidence on this conclusion is supplied by Ingerson and Ramisch (1942, pp. 595–606). They found that

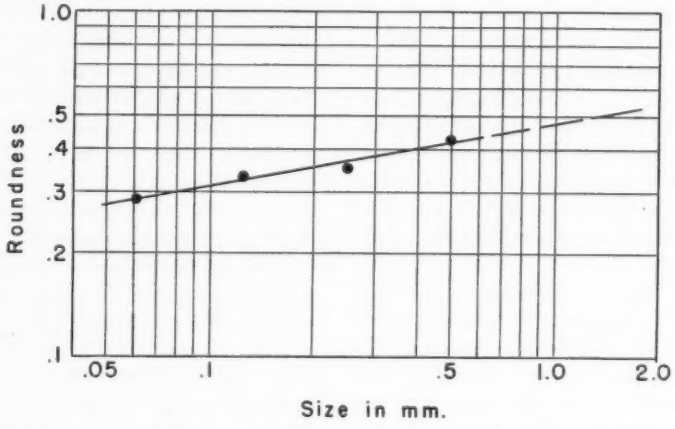


FIG. 28.—Relation of log arithmetic mean roundness and log geometric mean diameter. St. Peter sandstone (Wadell).

elongation of sand grains parallel to the *c*-axis (i.e., St. Peter sandstone) was a characteristic inherited from the parent igneous and metamorphic source rocks and not the result of abrasion and fracturing of the grains during transport.

On the other hand, Thiel's work (1940, pp. 103–124) offers evidence that sphericity change with abrasion is pronounced enough to provide a useful maturity index. He found that in 5,000 miles of transport the sphericity of quartz sand 1–2 mm. increased from 0.72 to 0.79. Three factors are important in evaluating the significance of this change. First, projection sphericities were measured and thus cannot be compared directly to true sphericity changes. Second, the sphericities of the artificially crushed quartz are considerably lower than those of natural quartz particles resulting from the breakup of igneous and metamorphic rocks. Third, the sphericity increased six times as fast in the last 3,000 miles as it did in the first 2,000 miles. This result is hard to explain on the basis of known facts of sphericity change, which would lead one to expect the greatest sphericity increase in the early stages of abrasion. Because Thiel's data contain factors unlike those of a natural environment and other evidence on sphericity change is contradictory to his conclusions, it is concluded that sphericity does not furnish a good index of maturity.

Unstable constituents of sand.—In this category, as an index of maturity, may be listed the percentages of feldspar and those heavy minerals which are mechanically and chemically unstable. Because the sand samples from the Black Hills were of a size too large to contain heavy minerals, the discussion will be limited to the feldspar percentage.

The graph of feldspar decrease with distance (fig. 24) suggests that the rate of feldspar decrease is a function of the stream gradient. The rapid feldspar decrease in Battle Creek is associated with the steep gradient of a mountain stream. A much slower decrease is associated with a gentler gradient of the Cheyenne River. Plots of these data on semilog paper reveal essentially straight lines. Thus, as a first approximation, it can be assumed that the rate of feldspar decrease follows an exponential law. Since data on feldspar decrease (1–1.414 mm.) are not available downstream in the Missouri and Mississippi rivers, it is possible to arrive at only a rough approximation of their effects on material of this size. If it were assumed that the exponential relation of feldspar decrease for the Cheyenne River held for the Missouri and Mississippi rivers and that no more feldspar was added, 1–1.414-mm. sand would have its feldspar content reduced to 14 per cent by the time it reached the Gulf of Mexico. Because the gradients of the Missouri and Mississippi rivers are much less than that of the Cheyenne River, it is probable that the feldspar decrease is not nearly so rapid as the above approximation indicates. R. D. Russell (1937, pp. 1307–1348) found that for somewhat smaller size grades in the Mississippi River the feldspar content varied irregularly with distance of transport. Some grades showed a feldspar decrease and others an increase. Thus it is apparent that, in spite of the rapid feldspar decrease of a sand near its source, one cycle of stream transport is not sufficient to produce an old-age feldspar index.

Gravel deposits.—Indices of maturity may also be applied to gravel deposits. Since abrasion affects large particles to a greater extent than it does small ones, it is to be expected that mature indices will be attained with less transport in the case of gravels than with sands.

The streams of the Black Hills are sup-

plied with gravel having very youthful maturity indices. Samples taken close to the foothills reveal youthful indices in terms of lithology but also mature indices in terms of rounding of some rock types. For example, gravel samples collected near the Dakota hogback average 35 per cent limestone and sandstone, a youthful index, but also contain well-rounded pebbles of quartz, a mature index. In Rapid Creek sample R-3 quartz pebbles 16–32 mm., after about 20 miles of transport, have an average roundness of 0.55. With a comparable distance of transport in Battle Creek, 1–1.414-mm. quartz sand has attained a roundness of only 0.31. It is evident from this comparison that a mature rounding index is more quickly reached in the case of large particles.

A gravel may be considered to have attained an index of old age when its component particles consist wholly of quartzose rocks (quartz, quartzite, chert) and those particles have reached their limit of rounding. The data suggest that mature indices are reached rather quickly in gravel deposits. In Rapid Creek 30 miles of transport have resulted in the loss of all but 2 or 3 per cent of the soft-rock components present in the gravels close to the Hills. In that distance the roundness of 16–32-mm. quartz pebbles has increased from 0.55 to 0.58. It is not possible, from the available data, to compute accurately the distance of transport necessary to reach the end of the maturity scale. However, from the chert ratio curves of figure 15 it is estimated that about 50 miles of transport would be required to remove essentially all but the quartzose rocks from the 16–32-mm. size class. The very slight increase in roundness from 0.55 to 0.58 in 30 miles suggests that the quartz pebbles have already approached an asymptotic roundness value in that distance.

It is apparent that the preceding discussion has only scratched the surface of the concept of "maturity indices." It is not sufficient to evaluate indices on the basis of any one size material, as has been done in the present work. The results obtained here suggest that a large range of sizes from many gravels and sands must be investigated from the maturity viewpoint before such a concept can become a practical tool for interpretation of clastic sediments. It is possible that further investigation may yield additional maturity indices. The degree of sorting of a sand or gravel or the standard deviation of roundness may furnish significant maturity criteria.

SUMMARY AND CONCLUSIONS

The study of detritus transported by streams draining the Black Hills has furnished a number of conclusions important to an understanding of sedimentary processes. Some of the conclusions presented here verify field results of other workers, some have been hinted at by laboratory investigators, and still others are contradictory, or supplementary, to prevailing ideas of the effects of stream transport on sedimentary particles.

In terms of size analysis the following conclusions have been drawn for streams similar to those of the Black Hills.

1. The mean size of a gravel deposit decreases with distance of transport. The decrease in mean size results primarily from a decreasing competence of the stream as the gradient decreases. A direct relationship exists between stream gradient and mean size, irrespective of whether or not the stream has a graded profile.

Quantitatively, selective transport accounts for 75 per cent of the size decrease in Rapid Creek and 84 per cent in Battle

Creek. The remaining percentages are accounted for by abrasion and breakage.

2. The skewness of the size distribution of a gravel deposit decreases with distance of transport. This decrease is a direct result of a decrease in the mean size.

3. The standard deviation or sorting of a gravel deposit shows no systematic change with distance of transport.

4. Secondary modes in the size distributions of Rapid and Bear Butte creeks are attributed to sand infiltration subsequent to deposition of the coarser material. Similar secondary modes of Battle Creek are attributed to inclusion of extensive sand layers in the channel samples.

Analysis of roundness and sphericity data yields the following conclusions:

1. The rounding of sedimentary particles may be expressed by the differential equation

$$\frac{dP}{dS} = KS^a(P_L - P),$$

which states that the rate of change of roundness with distance is directly proportional to some power (a) of the distance (S) and to the difference between the roundness (P) at any point and a limiting value of roundness (P_L). The constants of this equation (K and a) vary, depending on the composition and size of the particle, the rigor of transport to which it is subjected, and the size and composition of associated particles.

2. Sphericity change with distance shows a slight increase but is very erratic.

3. Quartz sand 1–1.414 mm. is definitely rounded in mountain streams of steep gradient. A 71 per cent increase in roundness is accomplished in the first 45 miles of transport.

4. Since both roundness and sphericity are related to size, they are related to each other. For 16–32-mm. limestone pebbles, a 12.3 per cent increase in sphericity is accompanied by a 380 per cent increase in roundness. Quartz sand 1–1.414 mm. yields a 119.1 per cent increase in roundness for a 4.7 per cent increase in sphericity.

Analysis of lithologic data leads to the following conclusions:

1. The initial lithologic frequency distribution of a gravel is directly related to the source area which furnishes detritus to a stream.

2. A short distance of stream transport removes most of the soft-rock types by abrasion and breakage. In a distance of 30 miles in Rapid Creek the percentage of limestone plus sandstone pebbles 16–32 mm. is reduced from 26.2 per cent to 2.6 per cent.

3. Loss of the softer rocks by abrasion and breakage during stream transport is a function of rigor of transport and size and composition of associated particles.

4. An order of resistance to abrasion and breakage is established for these streams. The rock types are listed in order of increasing resistance: sandstone, limestone-feldspar, pre-Cambrian metamorphics, quartz-quartzite, chert.

5. Mountain streams are very effective in reducing the feldspar content of coarse sands. A loss of 51.2 per cent in the feldspar content of 1–1.414-mm. sands resulted from a transport of 40 miles in Battle Creek. Transport of 150 miles in the Cheyenne River resulted in a 13.8 per cent decrease in feldspar content. This loss in feldspar can be attributed only to abrasion, breakage, and weathering during transport.

ACKNOWLEDGMENTS.—This work was made possible by the California Company Fellowship for research in sedimentology. The writer is also indebted to several individuals, whose

aid contributed to the carrying-out of the project. Mr. W. Schmidt, of the University of Chicago, helped design and construct sampling equipment for the field. Dr. George Otto, of the Armour Research Foundation, provided valuable information on techniques of field sampling. The writer's wife, Mrs. Donata Plumley, proved an indispensable assistant in the field work. Considerable aid in the mathematical treatment of pebble rounding was provided by Dr. Harold J. Plumley, of the Naval Ordnance Laboratory. Dr. L. Horberg, of the University of Chicago, suggested many helpful ideas on the interpretation of terraces. The writer is most indebted to Dr. F. J. Pettijohn, of the University of Chicago, whose helpful suggestions and criticisms have helped to carry the project through from its inception.

REFERENCES CITED

BARRELL, J. (1925) Marine and terrestrial conglomerates: Geol. Soc. America Bull. 36, pp. 279–342.

CROSBY, W. O. (1882) Geology of the Black Hills of Dakota: Boston Soc. Nat. History Proc., vol. 23, pp. 516–517.

DAKE, C. L. (1921) The problem of the St. Peter sandstone: Univ. Missouri School of Mines and Metallurgy Bull., Tech. Ser., vol. 6, chap. 2.

DARTON, N. H. (1899–1900) Preliminary description of the geology and water resources of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geol. Survey, 21st Ann. Rept., pt. 4, pp. 489–600.

——— (1909) Geology and water resources of the northern portion of the Black Hills: U.S. Geol. Survey Prof. Paper 65.

FENNEMAN, N. M. (1931) Physiography of western United States, New York, McGraw-Hill Book Co.

FILLMAN, L. (1929) Cenozoic history of the northern Black Hills: Univ. Iowa Studies in Nat. History, vol. 13, pp. 1–48.

FRASER, H. J. (1935) Experimental study of the porosity and permeability of clastic sediments: Jour. Geology, vol. 43, pp. 910–1010.

GRATON, L. C., and FRASER, H. J. (1935) Systematic packing of spheres—with particular relation to porosity and permeability: Jour. Geology, vol. 43, pp. 785–909.

INGERSON, E., and RAMISCH, J. L. (1942) Origin of shapes of quartz sand grains: Am. Mineralogist, vol. 27, pp. 595–606.

KELSH, H. T. (1940) The slotted-templet method for controlling maps made from aerial photographs: U.S. Dept. of Agr. Misc. Pub. 404, pp. 1–29.

KRUMBEIN, W. C. (1934) The probable error of sampling sediments for mechanical analysis: Am. Jour. Sci., vol. 27, pp. 204–214.

——— (1937) Sediments and exponential curves: Jour. Geology, vol. 45, pp. 577–601.

——— (1940) Flood gravel of San Gabriel Canyon, California: Geol. Soc. America Bull. 51, pp. 639–676.

——— (1941*a*) Measurement and geological significance of shape and roundness of sedimentary particles: Jour. Sedimentary Petrology, vol. 11, pp. 64–72.

——— (1941*b*) The effects of abrasion on the size, shape, and roundness of rock fragments: Jour. Geology, vol. 49, pp. 482–520.

——— (1942) Flood deposits of Arroyo Seco, Los Angeles County, California: Geol. Soc. America Bull. 53, pp. 1355–1402.

——— and PETTIJOHN, F. J. (1938) Manual of sedimentary petrography, New York, D. Appleton-Century.

——— and TISDEL, F. W. (1940) Size distribution of source rocks of sediments: Am. Jour. Sci., vol. 238, pp. 296–305.

KRYNINE, P. D. (1940) Petrology and genesis of the third Bradford Sand: Pennsylvania State Coll. Bull. 29.

KURK, E. H. (1941) The problem of sampling heterogeneous sediments: Unpublished Master's dissertation, Dept. of Geology, University of Chicago, pp. 1–37.

MACCLINTOCK, P. (1936) A Pleistocene lake in the White River Valley: Am. Naturalist, vol. 70, pp. 346–360.

MACKIE, W. (1896) The sands and sandstones of eastern Moray: Edinburgh Geol. Soc. Trans., vol. 7, pp. 148–172.

MEYERHOFF, H. A., and OLMSTEAD, E. W. (1937) Cenozoic leveling in the Black Hills (abstr.): Pan-Am. Geologist, vol. 68, p. 306.

NEWTON, H., and JENNEY, W. (1880) Geology of the Black Hills of Dakota: U.S. Geol. and Geog. Survey.

OTTO, G. H. (1933) Comparative tests of several methods of sampling heavy mineral concentrates: Jour. Sedimentary Petrology, vol. 3, pp. 30–39.

——— (1938) The sedimentation unit and its use in field sampling: Jour. Geology, vol. 46, pp. 569–582.

PERISHO, E. C., and VISHER, S. S. (1912) The geography, geology and biology of south-central South Dakota: South Dakota State Geol. and Biol. Survey Bull. 5, pp. 57–58.

PETTIJOHN, F. J., and LUNDAHL, A. C. (1943) Shape and roundness of Lake Erie beach sands: Jour. Sedimentary Petrology, vol. 13, pp. 69–78.

RUSSELL, R. D. (1937) Mineral composition of Mississippi River sands: Geol. Soc. America Bull. 48, pp. 1307–1348.

—— and TAYLOR, R. E. (1937) Roundness and shape of Mississippi River sands: Jour. Geology, vol. 45, pp. 225–267.

RUSSELL, W. L. (1929) Drainage alignment in the western Great Plains: Jour. Geology, vol. 37, pp. 249–255.

SARMIENTO, A. (1945) Experimental study of pebble abrasion: Unpublished Master's dissertation, Dept. of Geology, University of Chicago, pp. 1–59.

SHULITS, S. (1941) Rational equation of river-bed profile: Am. Geophys. Union Trans., 22d Ann. Meeting, pt. 2, pp. 622–630.

THIEL, G. A. (1940) The relative resistance to abrasion of mineral grains of sand size: Jour. Sedimentary Petrology, vol. 10, pp. 103–124.

TODD, J. E. (1900) A preliminary report on the geology of South Dakota: South Dakota Geol. Survey Bull. 1, pp. 120–121.

—— (1902) Hydrographic history of South Dakota: Geol. Soc. America Bull. 13, pp. 27–40.

—— (1923) Is the channel of the Missouri River through North Dakota of Tertiary origin?: Geol. Soc. America Bull. 34, pp. 491–493.

TWENHOFEL, W. H. (1945) The rounding of sand grains: Jour. Sedimentary Petrology, vol. 15, pp. 59–71.

UDDEN, J. A. (1914) Mechanical composition of clastic sediments: Geol. Soc. America Bull. 25, pp. 736–737.

WADELL, H. (1935) Volume, shape, and roundness of quartz particles: Jour. Geology, vol. 43, pp. 276–277.

WANLESS, H. R. (1923) The lithology and stratigraphy of the White River beds of South Dakota: Am. Philos. Soc. Proc., vol. 62, pp. 190–269.

WENTWORTH, W. C. (1919) A laboratory and field study of cobble abrasion: Jour. Geology, vol. 27, pp 507–522.

—— (1926) Methods of mechanical analysis of sediments: Univ. Iowa Studies in Nat. History, vol. 2, no. 2.

THE UNIQUE ASSOCIATION OF THALLIUM AND RUBIDIUM IN MINERALS[1]

L. H. AHRENS
Massachusetts Institute of Technology

ABSTRACT

Spectrochemical analyses of various minerals has shown that "alkali-metal" thallium and rubidium are found only in potassium minerals and the cesium mineral, pollucite, and that in these minerals the Tl:Rb association is very close. Altogether, 167 specimens have been analyzed quantitatively, the selection comprising lepidolite, amazonite, hydrothermal pegmatitic microcline, primary pegmatitic microcline, zinnwaldite, biotite, muscovite, phlogopite, pollucite, rhodizite, and cesium beryl. The mean weight percentage ratio of Rb_2O/Tl_2O was determined as 100; and the vast majority of the ratios fall within the limits of 35–300: the extreme limits are 10 and 650. A plot of log percentage of Rb_2O versus log percentage of Tl_2O produced a curve of unit slope over a thousand fold range of concentration that could be investigated. There thus appears to be no shift in the ratio Rb/Tl throughout the selective crystallization of minerals, and the ratio seems to be independent of type of host mineral; the ratio does, however, vary to some extent from area to area. The reasons for the close association of alkali-metal thallium and rubidium are that the radii of their ions are identical and that in certain pertinent respects their chemical properties are very similar.

With the possible exception of the pair Zr:Hf, which are very closely associated in minerals, alkali-metal thallium and rubidium are perhaps the most closely associated pair of elements in the earth's crust, and their association is all the more remarkable because thallium is a Group 3*b* element, whereas rubidium is an alkali metal (Group 1*a*).

The abundance of thallium in the earth's crust has been estimated as 0.0003 per cent by weight.

INTRODUCTION

Soon after its discovery in 1861 by Sir William Crookes, chemists recognized the peculiar chemical characteristics of thallium which led Dumas, even in 1862, to dub this element the "ornithorhynchus" (the duckbill platypus) among the elements because of its paradoxical properties. It was soon found to be omnipresent, but in very small amounts, in several sulphide minerals and in a few as a major constituent; for example, crookesite $(Cu, Tl, Ag)_2Se$, lorandite $(TlAsS_2)$; and hutchisonite $(Tl, Ag, Cu)_2S \cdot Pbs \cdot 2As_2S_3$.

Thallium had also been found in some potassium minerals such as mica and feldspar, where, in considerable contrast to its distribution referred to above, it was thought that thallium entered potassium minerals by substituting for potassium. In this paper the geochemistry of thallium in its latter role, that is, simulating an alkali metal ("alkali-metal" thallium) is discussed. Quantitative abundance data are given on its distribution in most potassium minerals and the cesium mineral, pollucite; and, in particular, the association of thallium with rubidium has been investigated in these minerals.

Because thallium is a Group 3*b* element in the Periodic Table and, as will be shown later, because its association with rubidium is very close and unique, some pertinent aspects of the chemistry of this element will be examined as an aid to understanding its geochemistry.

CHEMISTRY OF THALLIUM

Electronic configurations of each of the typical Group 3 elements and also the Group 3*b* elements are given in table 1.

Each of these elements has potentially three valence electrons (*s*- and *p*-orbits). In boron these three valence electrons are extremely tightly bound; but, with the

[1] Manuscript received March 9, 1948.

increase in the size of the atoms of the elements of higher atomic weight, the outer valence electrons become more loosely held, and variable valences are exhibited. In thallium the residual positive charge from the nucleus is weakest: the two 6*s* electrons tend to behave as an inert pair, and the completed shells plus the 6*s* electrons (gold core) are relatively stable, with the result that in contrast to other Group 3 elements, thallium is characteristically univalent. Lead, which follows thallium, shows a similar phenomenon, and divalent stable lead salts are common. The formation of a stable monovalent thallous ion, in place of a trivalent one, causes a marked expansion in size. The radius of Tl^+ = 1.49 A, which radius equals that of Rb^+. Next to Cs (radius = 1.69 A) these ions are the largest cations. As the ionic radii of Tl^+ and Rb^+ are identical, the facility with which the two ions enter lattice hosts should be very similar.

In certain respects which are of geochemical significance, thallous thallium exhibits chemical properties almost identical with those of the ions of the alkali metals of higher atomic weight. Tl^+ is a typical large-sized cation and in aqueous solution forms a soluble hydroxide, TlOH, which is a caustic alkali of similar strength to NaOH, KOH, etc. Thallium differs from the alkali metals in the formation of a sparingly soluble sulphide and chloride. Its sulphate and carbonate and most other thallium compounds are very similar to those of the alkali metals.

Since Tl^+ and Rb^+ have identical radii and as the chemical properties of these two elements are very similar in many important respects, thallium and rubidium should be very closely associated in most minerals, that is, in those minerals in which precipitation of thallous sulphide or chloride is not likely to occur. This investigation has been confined in the main, therefore, to silicate minerals of igneous origin.

TABLE 1

ELECTRONIC CONFIGURATIONS

Element	Atomic Number	K	L		M			N				O			P			(Shell)
		1*s*	2*s*	2*p*	3*s*	3*p*	3*d*	4*s*	4*p*	4*d*	4*f*	5*s*	5*p*	5*d*	6*s*	6*p*	6*d*	(Orbit)
B	5	2	2	1	....	....	....	....	....	....	....	....	....	....	....	....	....	.....
Al	13	2	2	6	2	1	....	....	....	....	....	....	....	....	....	....	....	.....
Ga	31	2	2	6	2	6	10	2	1	....	....	....	....	....	....	....	....	.....
In	49	2	2	6	2	6	10	2	6	10	....	2	1	....	....	....	....	.....
Tl	81	2	2	6	2	6	10	2	6	10	14	2	6	10	2	1	....	.....

It may be recalled that, although some other pairs of elements have reasonably close chemical properties and have ionic radii which are listed as identical or very nearly so, their geochemical association is not unusually close. The pair, nickel: magnesium, is an example, but it is known that, whereas the Mg^{++}-anion bond is essentially ionic, the Ni^{++}-anion bond is partly covalent, thereby causing an apparent decrease in the size of Ni^{++}. The pair, zirconium:hafnium, have ions of identical size and show the same type of bonding, and hence these two elements are very closely associated in minerals. In silicate minerals, the Rb^+-anion bond and Tl^+-anion bond are undoubtedly ionic, and one may regard the effective radii of Rb^+ and Tl^+ as equal.

SELECTION OF MINERALS FOR ANALYSIS

A preliminary qualitative spectrochemical survey of several minerals corroborated earlier evidence of the presence of thallium and rubidium in all potassium minerals and also in the cesium mineral, pollucite. In sodium-rich minerals, only occasionally could slight traces of rubidium and thallium be detected. The selection therefore comprises chiefly potassium minerals of various types, some specimens of pollucite, a few specimens of sodium minerals, and a few other types. Reference to the analytical data given in table 2 provides details of the minerals analyzed.

ANALYTICAL PROCEDURE

All analyses of thallium and rubidium were made spectrochemically. A description of the spectrochemical procedure employed has been given in an earlier paper by the author (1945) on the geochemical association of thallium and rubidium.

Most analyses were made on the large quartz spectrograph of the Government Metallurgical Laboratory, University of the Witwatersrand, Johannesburg, and about twenty-five specimens were analyzed with a large-grating instrument of the Department of Geology, Massachusetts Institute of Technology. The large dispersion (2.5 A/mm) of the latter instrument was necessary for analyzing biotite, in the analysis of which iron caused excessive interference when quartz optics were used.

ANALYTICAL RESULTS

The quantities of thallium and of rubidium found in the mineral specimens, together with the respective Rb_2O/Tl_2O, ratios (by weight percentage) are given in table 2. In addition to these analyses, Adamson (1942) has determined thallium and rubidium in a specimen of hydrothermal microcline from Varuträsk, Sweden, and found 2.1 per cent Rb_2O and 0.02 per cent Tl_2O; ratio $RB_2O/Tl_2O=100$.

DISCUSSION OF TABLE 2

VARIATION OF THE PERCENTAGE RATIO Rb_2O/Tl_2O IN GENERAL

In all, 167 ratios could be determined. The change in ratio is best shown graphically, and figure 1 shows the percentage of Rb_2O plotted against the percentage of Tl_2O, using log co-ordinates. A straight line of unit slope fits the points most satisfactorily, and, throughout the concentration range of about one thousand which could be investigated, there is no apparent change in the ratio, the mean value being, according to the graph, very nearly 100; the corresponding atomic ratio, Rb/Tl, is equivalent to 225. The value of this ratio seems to be independent of the host mineral but appears to vary from area to area and sometimes with a particular phase of mineralization, about which more will be said later.

As a reasonably large number of analyses were available, an attempt was made to draw a probability (known also as "normal" or "Gaussian") curve. If an accurate curve of this type can be drawn, a determination may be made of the frequency with which different values of the ratio Rb_2O/Tl_2O deviate from the mean, the value of which may be obtained from this curve. Figure 2 is a plot of frequency (ordinate) with which the ratio Rb_2O/Tl_2O falls within a definite interval in the ratio versus the logarithm (to base 10) of the ratio, plotted at each interval. An interval factor of 1.4 was found convenient, and each interval used and the frequency with which the ratio fell within the limits of each interval are tabulated in table 3; from these data figure 2 was plotted.

TABLE 2

No.	Locality	Per Cent Rb_2O	Per Cent Tl_2O	Rb_2O/Tl_2O	Per Cent K_2O
	A. Potash Feldspar				
1. *Pegmatitic**					
1	Mica Siding, E. Transvaal, S. Africa	0.022	0.00038	60	.....
2	Mica Siding, E. Transvaal, S. Africa	0.024	0.00037	65	.....
3	Mica Siding, E. Transvaal, S. Africa	0.018	0.00027	70	.....
4	W. of Kaleka, Krug. Nat. Pk., S. Africa	0.013	0.00017	75	.....
5	N. of Letaba River causeway, Krug. Nat. Pk., S. Africa	0.0075	0.00008	90	.....
6	N. of Letaba River, etc.	0.010	0.00012	80	.....
7	S. of Loole Kop, E. Transvaal	0.005	0.00005	100	.....
8	Major, Klein Letaba area, E. Transvaal	0.011	0.00010	110	.....
9	Olifantsrivierspoort, E. Transvaal	0.0045	0.000055	80	.....
10	Cotton Kop, E. Transvaal	0.022	0.00005	440	.....
11	Loole Kop, E. Transvaal	0.024	0.00006	400	.....
12	Loole Kop, E. Transvaal	0.020	0.00005	400	.....
13	Loole Kop, E. Transvaal	0.024	0.00009	270	.....
14	Palabora, E. Transvaal	0.018	0.00005	360	.....
15	Loole Kop, E. Transvaal	0.013	0.00005	260	.....
16	W. of Loole Kop, E. Transvaal	0.033	0.00005	650	.....
17	Palabora, E. Transvaal	0.025	0.00005	500	.....
18	Palabora, E. Transvaal	0.015	0.00004	400	.....
19	S.W. of Shangaan, E. Transvaal	0.015	0.00006	250	.....
20	S.W. of Shangaan, E. Transvaal	0.020	0.00005	400	.....
21	S.W. of Shangaan, E. Transvaal	0.025	0.00005	500	.....
22	S.W. of Shangaan, E. Transvaal	0.033	0.00010	330	.....
23	Letaba area, E. Transvaal	0.011	0.00004	300	.....
24	Johannesburg, Transvaal	0.077	0.00052	150	.....
25	Johannesburg, Transvaal	0.088	0.00062	140	.....
26	Johannesburg, Transvaal	0.078	0.00060	130	.....
27	Johannesburg, Transvaal	0.060	0.00050	120	.....
28	Johannesburg, Transvaal	0.058	0.00058	100	.....
29	Johannesburg, Transvaal	0.28	0.0021	130	.....
30	Johannesburg, Transvaal	0.066	0.00060	110	.....
31	Johannesburg, Transvaal	0.040	0.00060	70	.....
32	Mulder's Drift, near Johannesburg	0.033	0.00034	100	.....
33	Mulder's Drift, near Johannesburg	0.035	0.00033	110	.....
34	Rhenoster Spruit, Waterburg, Transvaal	0.028	0.00016	180	.....
35	Mutue Fides, Transvaal	0.030	0.00010	300	.....
36	Leeuwpoort Tin Mine, Transvaal	0.018	0.00010	180	.....
37	Messina, Transvaal	0.014	0.00010	140	.....
38	S. of Port Shepstone, Natal, S. Africa	0.010	0.00016	60	.....
39	Near Umgeni Dam, Natal, S. Africa	0.015	0.00005	300	.....
40	Oribi Gorge, Natal, S. Africa	0.019	0.00012	160	.....
41	Valley of 1,000 Hills, Natal, S. Africa	0.009	0.00025	40	.....
42	Illovo River, Mid-Illovo, Natal, S. Africa	0.020	0.00032	70	.....
43	Illovo River, Mid-Illovo, Natal, S. Africa	0.0084	0.00025	35	.....
44	Illovo River, Mid-Illovo, Natal, S. Africa	0.005	0.00013	40	.....
45	Illovo River, Mid-Illovo, Natal, S. Africa	0.006	0.00012	50	.....
46	Gordonia, NW. Cape Province, S. Africa	0.008	0.00016	55	.....
47	Henkries Valley, Namaqualand, S. Africa	0.037	0.00031	120	.....
48	Uranoop River area, Namaqualand, S. Africa	0.060	0.00072	80	.....
49	Uranoop River area, Namaqualand, S. Africa	0.043	0.00044	100	.....
50	Uranoop River area, Namaqualand, S. Africa	0.050	0.00069	70	.....
51	Uranoop River area, Namaqualand, S. Africa	0.012	0.00014	90	.....
52	Uranoop River area, Namaqualand, S. Africa	0.017	0.00016	100	.....
53	Uranoop River area, Namaqualand, S. Africa	0.056	0.00056	100	.....
54	Uranoop River area, Namaqualand, S. Africa	0.047	0.00050	90	.....
55	Bantry Bay, Cape Province, S. Africa	0.019	0.00033	60	.....

* Chiefly microcline and perthite.

TABLE 2—*Continued*

No.	Locality	Per Cent Rb_2O	Per Cent Tl_2O	Rb_2O/Tl_2O	Per Cent K_2O
	A. Potash Feldspar—*Continued*				
2. *From granite*					
56	Loole Kop, E. Transvaal, S. Africa	0.006	0.00008	75	.....
57	N.E. of Loole Kop, Transvaal, S. Africa	0.009	0.00011	80	.....
58	Mashishimala Hills, Transvaal, S. Africa	0.007	0.00007	100	.....
3. *Hydrothermal microcline from pegmatite*†					
59	Harding Mine, Dixon, New Mexico	0.21	0.005	40	.....
60	Harding Mine, Dixon, New Mexico	0.68	0.019	35	.....
61	Harding Mine, Dixon, New Mexico	0.41	0.013	30	.....
4. *Amazonite*					
62	Honeydew, Zoutpansberg, Transvaal	0.82	0.0052	160	.....
63	Klein Spitzkop, SW. Africa	0.15	0.0010	150	.....
64	Klein Spitzkop, SW. Africa	0.13	0.0010	130	.....
65	Klein Spitzkop, SW. Africa	0.20	0.0012	170	.....
66	Klein Spitzkop, SW. Africa	0.17	0.0010	170	.....
67	Maltahöhe, SW. Africa	0.33	0.0031	110	.....
68	Otjiwarongo, SW. Africa	0.44	0.0018	240	.....
69	Xamchab, Namaqualand, S. Africa	0.22	0.0016	140	.....
70	Gordonia, NW. Cape Province	0.25	0.0020	120	.....
71	Madagascar	1.30	0.0036	360	.....
72	Labrador	0.13	0.0010	130	.....
73	Norway	0.40	0.0080	50	.....
74	Ontario, Canada	0.33	0.0010	330	.....
75	Pike's Peak, Colorado	1.30	0.0052	260	.....
76	Florissant, Colorado	0.19	0.00062	300	.....
77	?	0.07	0.00062	110	.....
5. *Unclassified*					
78	Sweden	0.025	0.00041	60	.....
79	New Jersey	0.013	0.00034	35	.....
80	Baveno, Italy (orthoclase)	0.055	0.00062	90	.....
81	Wehr-Eifel, Germany	0.010	0.00003?	350?	.....
82	St. Gothard, Switzerland	0.026	0.00062	40	.....
83	?	0.014	0.00013	110	.....
84	?	0.015	0.00034	45	.....
85	?	0.023	0.00010	230	.....
	B. Plagioclase, Chiefly Albite‡				
86	Bandolier Kop, Transvaal	0.003?	.....	.....	0.23
87	Steinkopf Reserve, Namaqualand	.....	.....	.....	0.10
88	Uranoop River, Namaqualand	.....	.....	.....	0.10
89	Uranoop River, Namaqualand	.....	.....	.....	0.10
90	Uranoop River, Namaqualand	.....	.....	.....	0.22
91	Uranoop River, Namaqualand	.....	.....	.....	0.20
92	Uranoop River, Namaqualand	.....	.....	.....	0.10
93	Selati River, NE. Transvaal	.....	0.00004	.....	0.20
94	Warmbad, SW. Africa	0.012	0.0003	40	0.28
95	Karibib, SW. Africa	0.002?	0.00003?	.....	0.10
96	Sea Point, Cape Province	.....	.....	.....	0.80
97	Southern Rhodesia	0.002?	.....	.....	0.40
98	Southern Rhodesia	.....	.....	.....	1.0

† These three specimens have been listed as hydrothermal. According to A. Montgomery (private communication), who collected the specimens, the latter two specimens, one of which is very pale green and similar to amazonite, are of late formation and are believed to be hydrothermal. The first specimen is considered to be of earlier formation and could probably be better included with the common (primary) microcline group.

‡ To show the essentially sodic nature of these feldspars, the K_2O contents (determined spectrochemically) are also included.

TABLE 2—*Continued*

No.	Locality	Per Cent Rb_2O	Per Cent Tl_2O	Rb_2O/Tl_2O	Per Cent K_2O
	C. Lepidolite				
99	Okongava Ost 72, Karibib, SW. Africa	1.80	0.023	70	.....
100	Okongava Ost 72, Karibib, SW. Africa	1.30	0.016	80	.....
101	Albrecht's Höhe, SW. Africa	0.88	0.017	50	.....
102	Omaruru, SW. Africa	2.40	0.013	180	.....
103	Otjimboyo, SW. Africa	0.90	0.016	55	.....
104	Arandis, SW. Africa	0.47	0.010	50	.....
105	Warmbad, SW. Africa	1.60	0.016	100	.....
106	Jackalswater, Namaqualand	1.80	0.0052	350	.....
107	Jackalswater, Namaqualand	2.00	0.0060	350	.....
108	Mozambique, E. Africa	1.90	0.019	100	.....
109	Harding Mine, Dixon, New Mexico				
110	Harding Mine { low lithia content	0.41	0.011	35	.....
	Harding Mine { high lithia content	1.0	0.022	45	.....
111	Portland, Connecticut	0.78	0.010	80	.....
112	Strickland Quarry, Connecticut	0.55	0.0074	75	.....
113	Pala, California	2.00	0.021	100	.....
114	Pala, California	2.00	0.018	110	.....
115	Norway, Maine	1.70	0.016	110	.....
116	Auburn, Maine	0.87	0.016	55	.....
117	Black Hills, South Dakota	1.30	0.0062	210	.....
118	Black Hills, South Dakota	1.30	0.009	150	.....
119	Brown Derby, Colorado	2.80	0.024	120	.....
120	Brown Derby, Colorado	2.60	0.028	90	.....
121	Copper Mt., N. of Bonneville, Wyoming	1.40	0.010	140	.....
122	Along Winnipeg River, SE. Manitoba	1.60	0.017	100	.....
123	Lake of the Woods, SE. Manitoba	1.20	0.013	90	.....
124	Silver Leaf Mine, Winnipeg River, SE. Manitoba	2.90	0.012	240	.....
125	Lipowka, Urals	1.50	0.010	150	.....
126	Moravia	1.45	0.013	110	.....
127	?	1.70	0.019	90	.....
	D. Biotite (Lithium-rich from Pegmatite)				
128	Strickland Quarry, Connecticut	0.47	0.0084	55	.....
129	King's Mt., North Carolina	1.40	0.040	35	.....
	E. Zinnwaldite				
130	Saxony, Germany	0.66	0.0075	90	.....
131	Erzgebirge, Germany	0.35	0.0065	55	.....
132	Virginia	0.45	0.0074	60	.....
	F. Muscovite				
133	Mica Siding, E. Transvaal	0.066	0.0010	70	.....
134	Mica Siding, E. Transvaal	.....	.....	.....	.....
135	Olifants River, E. Transvaal	0.050	0.0012	40	.....
136	Game Reserve, E. Transvaal	0.15	0.0028	55	.....
137	Selati River, E. Transvaal	.....	.....	.....	.....
138	Near Leydsdorp, E. Transvaal	.....	.....	.....	.....
139	Olifants River, E. Transvaal	0.027	0.00034	80	.....
140	South of Usakos, SW. Africa	0.044	0.00062	70	.....

TABLE 2—*Continued*

No.[1]	Locality	Per Cent Rb_2O	Per Cent Tl_2O	Rb_2O/Tl_2O	Per Cent K_2O
	F. Muscovite—*Continued*				
141	South of Usakos, SW. Africa	0.049	0.00070	70	.....
142	Uranoop River area, Namaqualand	0.096	0.0030	30	.....
143	Uranoop River area, Namaqualand	0.045	0.0011	40	.....
144	Uranoop River area, Namaqualand	0.14	0.0035	40	.....
145	Uranoop River area, Namaqualand	0.10	0.0030	30	.....
146	Uranoop River area, Namaqualand	0.053	0.0014	40	.....
147	Uranoop River area, Namaqualand	0.10	0.0025	40	.....
148	Uranoop River area, Namaqualand	0.087	0.0023	40	.....
149	Uranoop River area, Namaqualand	0.010	0.00021	50	.....
150	Uranoop River area, Namaqualand	0.011	0.00031	35	.....
151	Uranoop River area, Namaqualand	0.063	0.0017	35	.....
152	Uranoop River area, Namaqualand	0.045	0.0010	45	.....
153	Uranoop River area, Namaqualand	0.066	0.0019	35	.....
154	Steinkopf Reserve, Namaqualand	0.46	0.0024	190	.....
155	Near Steinkopf, Namaqualand	0.64	0.0060	110	.....
156	NW. Cape Province	0.008	0.0002	40	.....
157	NW. Cape Province	0.11	0.0025	40	.....
158	Illovo River, Mid-Illovo, Natal	0.042	0.0010	40	.....
159	Sea Point, Cape Province	0.17	0.0038	45	.....
160	Bantry Bay, Cape Province	0.02	0.00025	80	.....
161	George, Cape Province	0.022	0.00037	60	.....
162	Miami, Southern Rhodesia	0.028	0.00062	45	.....
163	Southern Rhodesia	0.025	0.00031	60	.....
164	Salisbury, Southern Rhodesia	0.30	0.0033	90	.....
165	Harding Mine, Dixon, New Mexico (rose muscovite)	0.17	0.015	12	.....
166	North Carolina	0.078	0.0023	35	.....
167	Pennsylvania	0.020	0.00057	35	.....
168	Tyrol	.....	.....	.....	.....
169	Italy	0.01	0.00020	50	.....
	G. Phlogopite and Vermiculitized Phlogopite				
170	Graphic granite vein in gabbroidal rock, Vlakfontein, Transvaal	0.035	0.00046	80	.....
171	Dunite pipe, Mooihoek, Transvaal	0.042	0.00031	140	.....
172	Palabora, Transvaal (in syenite)	0.072	0.00020	360	.....
173	Palabora, Transvaal (in syenite)	0.055	0.00012	420	.....
174	Palabora, Transvaal (in syenite)	0.050	<0.00010	.....	.....
175	Palabora, Transvaal (in syenite)	0.036	<0.00010	.....	.....
176	Palabora, Transvaal (in syenite)	0.012	.....	.....	.....
177	Palabora, Transvaal (in syenite)	0.005–0.01	.....	.....	.....
178	Palabora, Transvaal (in syenite)	.....	.....	.....	.....
179	Antwerp, New York	0.029	0.00029	100	.....
180	Ontario, Canada	0.012	0.00030	40	.....
	H. Pollucite				
181	Okongava Ost 72, Karibib, SW. Africa	0.54	0.011	50	.....
182	Tin Mt., Black Hills, S. Dakota	0.25	0.0019	130	.....
183	Greenwood, Maine	0.68	0.0019	350	.....
184	Norway, Maine	0.23	0.0013	180	.....
185	Varuträsk, Sweden	0.37	0.008	45	.....

TABLE 2—*Continued*

No.	Locality	Per Cent Rb_2O	Per Cent Tl_2O	Rb_2O/Tl_2O	Per Cent K_2O
	I. Sundry Minerals				
186.....	Beryl: Steinkopf Reserve, Namaqualand	.....	.....	.....	.....
187.....	Beryl: Manjak, Madagascar (contains 0.5% Cs_2O)	0.30	0.004	80	.....
188.....	Rhodizite: Manjak, Madagascar (contains 1.5% Cs_2O)	1.00	0.01	100	.....
189.....	Petalite: Karibib, SW. Africa	.....	.....	.....	.....
190.....	Amblygonite: Karibib, SW. Africa	.....	.....	.....	.....
191.....	Paragonite: Carinthia	.....	.....	.....	.....

The equation for a normal curve is

$$y = k\, e^{-h^2x^2},$$

where k is the height of the curve when x, the deviation from the mean, is equal to zero. The ordinate(y) is frequency. When $x = 0$, $y = k$. The symbol h is a constant which determines the slope of the curve for a given k. Using values of $k = 29$ and $h = 0.062$, which are obtained by trial, a normal curve may be drawn which closely fits the curve shown in figure 2. One may conclude, therefore, that the curve in figure 2, which was not drawn from calculation, shows a near-normal Gaussian distribution of events about a mean.

With the aid of this curve, the following data are given on the Rb_2O/Tl_2O ratio in igneous silicate minerals throughout the earth's crust as a whole (the mean ratio, Rb_2O/Tl_2O is 90):

$\frac{1}{2}$ all ratios lie within $\frac{2}{3}$–$\frac{3}{2}$ of the mean, namely, within 60–135,

$\frac{3}{4}$ all ratios lie within $\frac{1}{2}$–$\frac{3}{1}$ of the mean, namely, within 45–180,

$\frac{4}{5}$ all ratios lie within $\frac{1}{3}$–$\frac{3}{1}$ of the mean, namely, within 30–270,

$\frac{24}{25}$ all ratios lie within $\frac{1}{6}$–$\frac{5}{1}$ of the mean, namely, within 20–450,

$\frac{990}{1000}$ all ratios lie within $\frac{1}{10}$–$\frac{10}{1}$ of the mean, namely, within 10–900.

VARIATION OF THE RATIO Rb_2O/Tl_2O IN SPECIFIC AREAS

Reference to the analyses given in table 2 shows clearly that different areas are characterized by definite ratios. In certain areas several mineral specimens have been analyzed; the value of the Rb_2O/Tl_2O ratio will be discussed in some of these areas.

"Old Granite"[2] *area of the Olifants River.*—Ten specimens of feldspar and seven of muscovite (nos. 56, 1–9, 133–139 in table 2) were analyzed from this area. A few of the specimens are of doubtful association, that is, it is not quite clear whether they are genetically related to the "Old Granite" or to the syenites of the Palabora Complex. Because minerals that are definitely related to the "Old Granite" have typically low ratios, whereas those related to the Palabora syenites have characteristically high ratios, in cases of doubtful association where the ratios are low they are included with the "Old Granite," whereas where they are high they have been included with the Palabora syenite (Ahrens, 1945).

[2] In South Africa, the ancient granite-gneiss complexes are commonly referred to as the "Old Granite."

Almost within the limits of experimental error, the ratio Rb_2O/Tl_2O is constant, irrespective of the mineral type.

Uranoop River area, Namaqualand.—Twenty-four specimens (twelve of muscovite, seven of microcline, and five of albite) from the area between Uranoop Trig beacon I and the Uranoop River, Namaqualand, were very kindly collected by Dr. John de Villiers of the Geological Survey, Union of South Africa. In each instance feldspar and mica are associated in the same pegmatite, but each feldspar-mica pair comes from a different pegmatite. For convenience of discussion, the analyses of these specimens are given again in table 4.

Some interesting conclusions may be drawn from these results:

1. The ratio Rb_2O/Tl_2O is constant for all micas; indeed, this ratio is so constant that a plot of log Rb_2O versus log Tl_2O gives a straight line of unit slope, from which curve the plotted points deviate very slightly. In this example, as in others discussed under this subheading, the ratio Rb_2O/Tl_2O approaches a constancy of a ratio of isotopes, when some allowance is made for the experimental error.

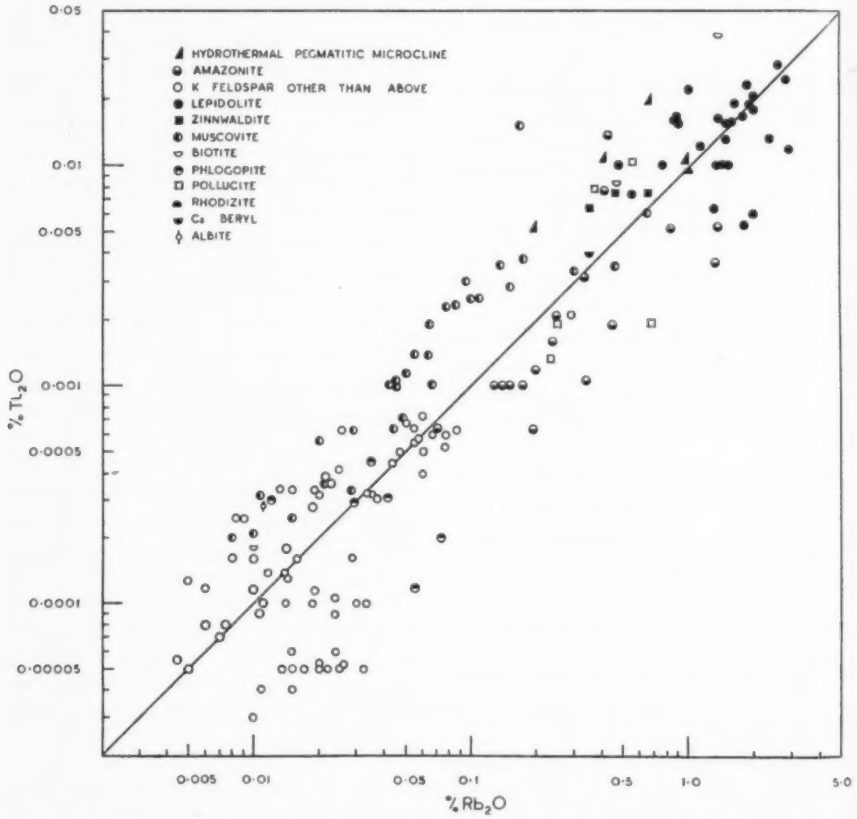


FIG. 1.—The relationship between thallium and rubidium in 167 mineral specimens of various types

2. The ratio Rb_2O/Tl_2O is constant for all microcline specimens but differs from the value of the mica ratio.

3. Those mica specimens associated with albite are usually richer in rubidium and thallium than are those associated with microcline.

4. The rubidium contents of microcline and associated mica are approximately the same in each instance.

as the mineral richest in alkali-metal thallium and rubidium. Mean values are 0.015 per cent Tl_2O and 1.5 per cent Rb_2O.

Amazonite and hydrothermal pegmatitic microcline.—In contrast to microcline from granite and the common primary-phase microcline from pegmatite, amazonite (considered to be hydrothermal) and hydrothermal pegmatitic microcline appear to be markedly enriched in thal-

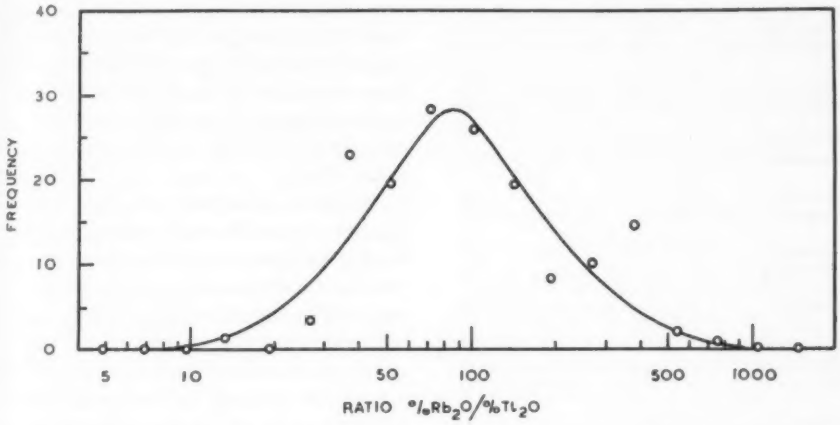


FIG. 2.—Normal (probability) curve, showing distribution of the variation of the ratio per cent Rb_2O: per cent Tl_2O about the mean.

5. Neither thallium nor rubidium could be detected in any of the five specimens of albite.

Further discussion of the Rb_2O/Tl_2O ratio in this area, as well as in the Palabora and the Usakos-Karibib areas, has been made by Ahrens (1945).

THE ABUNDANCE OF THALLIUM AND OF RUBIDIUM IN DIFFERENT MINERALS

A few comments will be made on the abundance of thallium and of rubidium in some of the minerals listed in table 2.

Lepidolite.—All specimens are characteristically enriched in thallium and rubidium, and lepidolite may be regarded

TABLE 3

Interval	Frequency
5.6– 7.9	0
8.9– 11.0	0
12.0– 15	1
16 – 22	0
23 – 30	3
31 – 42	23
43 – 59	19
60 – 83	28
84 – 116	26
117 – 162	19
163 – 223	8
224 – 317	10
318 – 445	14
446 – 620	2
621 – 870	1
871 –1200	0
1201 –1700	0
1701 –2400	0

lium and rubidium. Goldschmidt *et al.* (1934) have referred to the enrichment of rubidium in amazonite, although analyses by Erämetsä *et al.* (1941) of various specimens of microcline, including amazonite, do not support this characteristic enrichment of rubidium.

TABLE 4

Mineral	Per Cent Rb_2O	Per Cent Tl_2O	Rb_2O/Tl_2O
Microcline	0.06	0.00072	80
Muscovite	0.096	0.0030	30
Microcline	0.043	0.00044	100
Muscovite	0.045	0.0011	40
Microcline	0.050	0.00069	70
Muscovite	0.053	0.0014	40
Microcline	0.012	0.00014	90
Muscovite	0.010	0.00021	50
Microcline	0.017	0.00016	100
Muscovite	0.011	0.0031	40
Microcline	0.056	0.00056	100
Muscovite	0.063	0.00017	35
Microcline	0.047	0.00050	90
Muscovite	0.045	0.0010	45
Albite			
Muscovite	0.14	0.0035	40
Albite			
Muscovite	0.10	0.0030	30
Albite			
Muscovite	0.10	0.0025	40
Albite			
Muscovite	0.087	0.0023	40
Albite			
Muscovite	0.066	0.0020	35

Data on hydrothermal microcline from pegmatite are scant, but they do indicate strongly that thallium and rubidium are markedly enriched in this mineral relative to the primary type: in fact, if it can be substantiated by further research, this characteristic enrichment of rubidium and thallium in hydrothermal microcline should serve usefully for differentiating between common (primary) pegmatitic microcline and the later hydrothermal type.

Cognizance has, of course, to be taken of possible variation in the general abundance of rubidium and thallium in different petrographic provinces. For example, reference to table 2 shows that specimens of microcline (primary pegmatitic) from the Illovo River area, Natal (nos. 42–45) are unusually poor in thallium and rubidium (mean, 0.0002 per cent Tl_2O; 0.01 per cent Rb_2O), whereas in the Johannesburg area a much greater concentration of these two elements is found (mean, 0.0009 per cent Tl_2O and 0.1 per cent Rb_2O) in microcline of the same type.

Pollucite.—Pollucite may be regarded also as a hydrothermal replacement mineral in complex pegmatites, and, in common with all potassium-rich hydrothermal replacement minerals, this cesium mineral shows a characteristic enrichment of thallium and rubidium. The quantities of these two elements found appears to be of the same magnitude as that found in amazonite. In contrast, however, with the potassium minerals, Tl^+ and Rb^+ substitute for Cs^+ in pollucite in place of K^+ in potassium minerals.

Enrichment of thallium and rubidium relative to potassium in later hydrothermal replacement minerals accords well with theory: it will be recalled that a geochemical rule enunciated by Goldschmidt (1937) states that when two (or more) ions of like size proxy for a given lattice site in a growing crystal, the smaller (in this instance, K^+) ion is accepted more readily because of its greater electrostatic attraction, whereas the larger ions (Tl^+ and Rb^+) tend to be enriched in the residual mother liquor. This enrichment is extremely marked for cesium (radius $Cs^+ = 1.69$ A) because Cs^+ is larger than

Tl^+ and Rb^+; consequently, cesium may become highly concentrated in residual pegmatitic liquors, thereby causing a precipitation of the cesium mineral, pollucite. This accounts for the fact that, although cesium and rubidium are very similar chemically and although rubidium is much more abundant than cesium, rubidium never forms minerals of its own, whereas cesium does, on occasion, form pollucite.

Lithium-rich muscovite and biotite from complex pegmatites.—A marked enrichment of thallium and rubidium is characteristic of lithium-rich muscovite and biotite from complex lithium pegmatites. The enrichment of rubidium had been mentioned by Stevens and Schaller (1942), and Ahrens (1945) has shown graphically in a plot of log percentage Li_2O versus log percentage Rb_2O in muscovite that, although there is a considerable spread in the plotted points, the sympathetic trend in the concentrations of these two elements is quite apparent. Likewise, because of the very close association between thallium and rubidium, lithium and thallium show similar sympathetic trends. In muscovite, thallium and rubidium concentrations vary over considerable ranges.

Data for lithium-rich biotite are very scant, but in the specimen from North Carolina 0.04 per cent Tl_2O and 1.4 per cent Rb_2O were found; this amount of thallium is the highest reported in this investigation. In lithium-rich biotite from the Strickland Quarry, Connecticut, thallium and rubidium were also relatively enriched.

Common pegmatitic microcline.—In a high proportion of the specimens analyzed the concentrations of thallium and rubidium fall within limits of 0.01–0.1 per cent Rb_2O and 0.0001–0.001 per cent Tl_2O. Because of this wide variation in concentration of thallium and rubidium in these specimens, it is difficult to give accurate mean abundance values: approximate mean values are 0.0004 per cent Tl_2O and 0.04 per cent Rb_2O.

The rubidium contents of these microcline specimens appear, in general, to be less than reported elsewhere in the literature; until some interchecking has been done, it will not be possible to ascertain whether the reason lies in the nature of the selection analyzed or whether the discrepancy is due largely to analytical procedure.

In most other minerals, data on thallium and rubidium are very scant and have therefore not been discussed here.

ABUNDANCE OF THALLIUM IN THE EARTH'S CRUST

Goldschmidt (1937) gives 0.00003 per cent (by weight) as the abundance of thallium in the earth's crust. This value is based on the relatively scant data that were available at the time, and the results of this investigation indicate strongly that this abundance value is too low.

In granite and other rocks relatively rich in potassium, thallium determinations could not be made because the concentration was below the limit of detection of the spectrographic method employed. In arriving at a value for the abundance of thallium in the earth's crust, use may be made, however, of the close association of rubidium and thallium in potassium minerals and of our knowledge of the abundance of rubidium in the earth's crust. According to Goldschmidt (1937), the abundance of rubidium is 0.03 per cent by weight, which value, although possibly subject to some revision because of several more recent analyses, is probably of the correct magnitude. Consequently, using a value of

100 for the ratio Rb_2O/Tl_2O, the abundance of thallium in the earth's crust is calculated as 0.0003 per cent, a value which is greater than the older one by a factor of 10.

This value refers to alkali-metal thallium, but it is considered that sulphide thallium present as a trace in some sulphide minerals is insignificant in amount when compared with the thallium content of potassium silicates; consequently, the value of 0.0003 per cent may be regarded as applying to total thallium.

A COMPARISON OF THE PAIR Rb:Tl WITH OTHER PAIRS OF ELEMENTS

Other pairs of elements are closely associated in minerals: Al-Ga, Rb-K, Ni-Mg, Sr-Ba, Cb-Ta, sundry rare earth elements, and, in particular, Zr-Hf are examples. With the exception of Zr-Hf and possibly some of the rare earths, data on which are very meager, no other pairs of elements are known which are as closely associated as are alkali-metal thallium and rubidium in silicate minerals.

Zirconium and hafnium are very similar chemically and have identical ionic radii; as a result, they have very similar properties, so much so that the discovery of hafnium, which is always present in zirconium minerals, was much delayed. In the common zirconium mineral, zircon, the Zr/Hf ratio has been found to vary only relatively slightly; but in some of the more obscure zirconium minerals the ratio is more erratic. Unfortunately, data are not sufficient to permit a statistical analysis and obtain a normal (probability) curve to compare with the Rb_2O/Tl_2O normal curve. All that can be said now is that the pair Zr: Hf are very closely associated, the closeness of the association being probably similar to that of alkali-metal thallium and rubidium.

The association of zirconium with hafnium differs, however, in some respects from the association of rubidium with thallium; zirconium is a major constituent and forms its own minerals, in which hafnium enters as a minor constituent. Neither rubidium nor alkali-metal thallium forms its own minerals; both elements proxy for potassium in potassium minerals and for cesium in pollucite. Furthermore, like nearly all other pairs of associated elements, zirconium and hafnium are placed close together in the Periodic Table, whereas rubidium is Group *1a* and thallium is Group *3b;* hence their very close association in minerals is therefore unique.

REFERENCES CITED

ADAMSON, O. J. (1942) Minerals of the Varuträsk pegmatite, XXI: The feldspar group: Geol. fören. Stockholm Förh., vol. 64, pp. 19–54.

AHRENS, L. H. (1945) The relationship between thallium and rubidium in minerals of igneous origin: Geol. Soc. South Africa Trans., vol. 48, pp. 207–231.

ERÄMETSÄ, O.; SAHAMA, T. G.; and KANULA, V. (1941) Spektrographische Bestimmungen an Rubidium und Caesium in einigen finnischen Mineralien und Gesteinen: Comm. géol. Finlande Bull. 128, pp. 80–86.

GOLDSCHMIDT, V. M. (1937) The principles of distribution of chemical elements in minerals and rocks: Chem. Soc. London Jour., pp. 655–673.

———; BAUER, H.; and WITTE, H. (1934) Zur Geochemie der Alkali-Metalle: Gesell. Wiss. Göttingen, Math.-phys. Kl., no. 1, pp. 39–55.

STEVENS, R. E., and SCHALLER, W. T. (1942) The rare alkalies in micas: Am. Mineralogist, vol. 27, pp. 525–537.

REVIEWS

Fine-grained Alluvial Deposits and Their Effects on Mississippi River Activity. By HAROLD N. FISK. War Department, Corps of Engineers, Mississippi River Commission, Vicksburg, Mississippi, July 1947. 2 Vols. Pp. 82, figs. 12, pls. 74. $1.25 per volume; $2.50 per set.

The first of these volumes contains the text and figures of the report, the second carries the 74 plates illustrating the text. Presentation of the problem is divided into four parts, which logically develop the author's ideas on the relations of Mississippi River activity to the finer-grained alluvial deposits along the river course.

The Mississippi River and its alluvial valley are discussed in a general way with regard to its physical geology and recent geologic history. Maps are included which show the entrenched valley system during late Wisconsin time and the river course at two later times before the present.

Fine-grained alluvial deposits along the river are described from the point of view of depositional environment, distribution, and physiographic expression. In the second volume a topographic map of the Mississippi River and part of its valley from Commerce Gorge in Missouri to Donaldsonville, Louisiana, is given at a scale of 1:125,000. On this map is shown the distribution and thickness of the fine-grained alluvial deposits as determined by boring and surface mapping. In addition, 359 cross sections are reproduced, showing the thickness and relations of these deposits.

The properties of the fine-grained alluvial deposits are discussed for each type of environment as to grain size, degree of sorting, size distribution within the deposits, and water content. Over fifteen thousand mechanical and hydrometer analyses of samples were made to obtain this information. A more complete list of physical properties is given for the back-swamp deposits, based on detailed testing for the Bayou Sorrell lock site. Detailed compilations of all these data are included in the second volume.

The effect of fine-grained alluvial deposits on Mississippi River activity is described in relation to channel migration, channel cross section, bank caving, stream meandering, and development of reaches.

Effective use is made of block diagrams in illustrating such features as valley development stages and bank caving. Aerial and close-up photographs are used to some extent; but, unfortunately, many of them are not very clear. This is probably due to the fact that they have not been reproduced on glossy paper.

This report is based on very extensive borings and areal mapping done by the Corps of Engineers and contains much authoritative information. It should prove very useful as a source of data on the fine-grained alluvial deposits of the Mississippi River and in supplementing the author's earlier *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*.

A. L. KIDWELL

Geological Explorations in the Island of Celebes under the Leadership of H. A. Brouwer. Amsterdam: North-Holland Pub. Co., 1947. Pp. 346, figs. 25, pls. 25, sketch maps 2. 27.50 gulden.

This volume is another valuable addition to the geology of the East Indian archipelago to which Dr. Brouwer and his associates have contributed so much. It is divided into three sections: "Geological Explorations in Celebes. Summary of the Results," by H. A. Brouwer; "Igneous and Metamorphic Rocks in Eastern Central Celebes," by W. P. de Roever; "Contribution to the Petrology of the Metamorphic Rocks of Western Celebes," by C. G. Egeler.

Celebes is divided into three main zones: (1) an eastern zone with abundant basic and ultrabasic igneous rocks, schists, Mesozoic and possibly older limestones, and siliceous rocks containing radiolaria; (2) a central zone of epidote mesometamorphic muscovite-rich schists, quartzites, and limestones; and (3) a western zone of granitic to dioritic rocks, gneisses, biotite-rich schists, and Mesozoic and Tertiary volcanic and sedimentary rocks.

The section by De Roever on east-central Celebes is largely descriptive. In a brief petrologic summary on the igneous rocks he concludes that they belong to one differentiation series

comparable with the ophiolite-spilite complex and the Palelo series in Netherlands Timor and to the igneous rocks in the Ligurid overthrust sheet of the Italian Apennines. The metamorphic rocks are classified into the glaucophane-schist and the epidote-amphibolite facies. The glaucophane schist facies is subdivided into two subfacies, one characterized by the stability of lawsonite and the instability of epidote and garnet (lawsonite-glaucophanite subfacies) and the other having the critical associations alkali-amphibole-epidote and alkaliamphibole-garnet with lawsonite unstable. The epidote-amphibolite facies is believed to represent a metamorphism which is older than the radiolarites and the ophiolite and spilitic igneous rocks; the glaucophane schist facies represents a younger metamorphism. Evidence is presented that pumpellyite belongs to a separate metamorphic facies "younger than the radiolarites and igneous rocks, but older than the glaucophanite metamorphism."

The section by Egeler on the rocks of western Celebes contains detailed descriptions of a great variety of metamorphic rocks. He groups these into four facies: greenschist, epidote-amphibolite, amphibolite, and granulite. The amphibolite facies predominates, and the author distinguishes three subfacies, with staurolite, andalusite, and sillimanite-cordierite. Egeler concludes that there were two periods of metamorphism, an older regional upon which was superimposed a younger plutono-metamorphism. The latter is characterized by granitic and granodioritic intrusions with associated intense injection activity and intermingling of igneous and contact rocks. A later low-grade dynamic metamorphism affected the granites.

The authors point out that the glaucophane metamorphism, in eastern Celebes is believed to belong to the same orogenic cycle as does the amphibolitic plutono-metamorphism in the western part. The glaucophane metamorphism and the granodiorite intrusion in the east are late Mesozoic to Tertiary, whereas the epidote-amphibolite metamorphism is older. The regional metamorphism and thermal metamorphism were separated by a long period of sedimentation and volcanic activity. The older group of regional metamorphic facies in the western part is correlated with the epidote-amphibolite metamorphism in the east. The regional metamorphism may have been accompanied by plutonic activity, i.e., some granite and granodiorite may represent this activity.

In his treatment of the structural geology of Celebes, Brouwer states: "From the central part of the Celebes geanticlines branch out to form the four peninsulas, which are separated by deep sea-basins." East of the median zone in Celebes the main strike of minor folds is north-northeast and north-northwest; near the median zone the strike is northeast and east-northeast. The major fractures and faults trend roughly north-south, except in the northeastern part, where they are, in general, east-west. Here the linear arrangement of active and extinct volcanoes shows that they are located on or near lines of fractures. Recent faulting has occurred, but these faults may have been active during long periods, and their age may be considerable.

Major uplift of the peneplane of central Celebes probably "took place in the youngest geological past. Subsidence in fault troughs, which were already in existence in Tertiary time, would then have preceded the general uplift." Brouwer discusses the theories of origin of the Celebes fault troughs and rift valleys.

The book is well printed and bound and has excellent illustrations, in particular the photomicrographs. It is to be regretted that, because of the German occupation, the authors were unable to obtain chemical analyses. Consequently, the parts of the book on petrologic interpretations and comparisons with similar areas are limited in scope. The book, nevertheless, is a worth-while contribution to the geology of Celebes, in particular the metamorphic and structural geology. As Brouwer states, the work is largely "an outline of a field for geological research, which is full of promise."

A. F. HAGNER

Guide to the Geology of Central Colorado. (*Colorado School of Mines Quart.*, vol. 43, no. 2.) 1948. Pp. 176. $3.00.

This volume contains the work of a number of contributors and is published in conjunction with the Rocky Mountain Association of Geologists. It contains road logs and articles covering the principal geologic features in connection with three field trips arranged for the American Association of Petroleum Geologists. The trips all start from Denver and include: (1) a one-day trip through Boulder, Golden, and Morrison; (2) a two-day trip along the Front Range to Colorado Springs (first day) and to Canyon City and Royal Gorge (second day); (3) a three-day trip along the Front Range, Mosquito-Gore

Range, Glenwood Canyon to Glenwood Springs (first day), to Rifle Gilman, Red Cliff, and Leadville (second day), and along the Arkansas Valley, across the Mosquito Range to South Park and Denver (third day).

The articles cover the general geology of central Colorado, the Kokomo, Gilman, Leadville, and Climax mining areas, and the oil-shale deposits near Rifle. Most of them are summaries or revisions of published papers. The United States Bureau of Mines oil-shale demonstration plant at Rifle is described. The volume contains thirty-eight geologic and columnar sections, maps, diagrams, and photographs. A map gives the routes of the trips, the major geologic structure, and oil and gas information. The bulk of the volume is devoted to road logs and to the stratigraphic and structural geology of central Colorado; it serves as a useful guide to the region.

A. F. HAGNER

Eruptive Rocks: Their Genesis, Composition, Classification, and Their Relation to Ore Deposits, with a Chapter on Meteorites. By S. J. SHAND. 3d ed. New York: John Wiley & Sons; London: Thomas Murby & Co., 1947. Pp. xvi+488; figs. 51; pls. 4. $7.50.

The first edition of Professor Shand's book (1927) marked a new approach to many petrological problems and soon established itself as a particularly valuable guide for the novice as well as the expert.

In the third edition the content has been rearranged, in that the chapters of modal analyses of rocks, which are intended to illustrate Shand's well-known system of classification, have been moved to the end of the book, where they form Part II. This is an improvement. The book is now exceptionally well written, interesting, and logical in its setup.

Three new chapters have been introduced to bridge the gap between eruptive rocks and certain types of ore deposits. Much valuable information has been collected. The subject matter, including such highly controversial problems as the genesis of pegmatites and late magmatic and postmagmatic reactions, is logically and clearly presented. There are no wild speculations, each statement is carefully considered and supported by thoroughly checked facts.

Professor Shand's superior insight and intimate knowledge of the eruptive rocks makes this new edition a source of information of great value to our science.

However, when reading this book, a rather fundamental question in the teaching of petrology insinuated itself into my thoughts. A couple of examples will illustrate the problem.

Shand's discussion of the order of crystallization is purely descriptive; no effort is made to present and use the elementary laws of physical chemistry. In my opinion it is much easier for the student to understand and remember the facts if they are logically related to fundamental natural laws. Shand completely avoids any use of mathematical symbols; thus his descriptions become so qualitative as to be inaccurate. It is *not* true that "leucite is compatible with free silica above 1170° C" (pp. 99 and 122); and the "simplified" diagram of MgO–SiO_2 (p. 223) is radically wrong. The phenomenon of incongruent melting, so fundamental in petrogenesis, cannot be understood at all from such oversimplified statements.

Likewise, the section on geologic thermometry (chapter on temperature and pressure in the magma) is purely descriptive and conspicuously lacking in quantitative background. Much space is devoted to telling what this and that geologist thought about the influence of pressure on the inversion-point quartz-tridymite; but the reader is never taught that there is a very important thermodynamic relation concerning the equilibrium between phases called "Clapeyron's equation."

Are petrology students really so deficient in general scientific background as to be unable to appreciate the great simplification introduced by a thermodynamic equation? I do not think so. And if some students are, they should be required to make up for such deficiencies.

Professor Shand has a fascinating way of teaching the petrology of eruptive rocks. Outdated notions are left behind like dead wood, and a treatment has been introduced which is, to a large extent, based on the chemistry of silicate systems. Yet nobody can adequately teach the chemistry of such systems without making use of the fundamental laws of thermodynamics.

T. F. W. B.

Biography of the Earth. By GEORGE GAMOW. New York: New American Library, 1948. Pp. xiii+194. $0.35.

This is a pocket edition of the popular book, first published in 1941, with the addition of a section to the chapter on the origin of the earth.

The volume is directed at the nonscientific reader, and the author does a good job of putting into everyday language the astronomical and geological facts of the story. Geologists will find minor points on which they will disagree with the author (as well as among themselves) and will feel that he tends to put too much reliance on deductions drawn from facts which may themselves be poorly established. On the whole, however, the book is accurate as well as entertaining. The Preface indicates that misstatements and misprints in the original edition have been corrected, but a few still remain. An example is the statement that the term "Cambrian" comes from the eastern England county, instead of Cambria, Wales. Erosion is stated to have removed a 4-inch layer from the surface of the United States since Columbus landed in the New World, although the rate of denudation is given (correctly) as about 0.02 mm. per year —or $\frac{3}{4}$ inch since 1492.

American readers would prefer American rather than English spellings where these differ, and the reviewer feels that well-chosen references to guide the reader further into many of the fields touched upon would be valuable. The author succeeds in rousing an interest in every phase of his subject, which ought to be encouraged by suggested readings.

M. S. C.

Gem Testing. By B. W. ANDERSON. New York: Emerson Books, 1948. Pp. 256; figs. 53. $5.00.

The purpose of this work is to serve as "a simple yet detailed manual for jewelers and others who are interested in the identification of gem stones." The earlier chapters cover refractometry and immersion index methods, the dichroscope, specific gravity, the microscope, and the spectroscope. There is a color plate showing absorption spectra. The remainder of the book deals with the identification of the various gem stones, synthetic and natural. An appendix contains a glossary of terms, lists of properties, etc. There is an index. There are a number of good photomicrographs, and the technical job of bookmaking is well done. The book would seem to fulfil its objective in praiseworthy fashion; it is recommended for the serious nonspecialist.

D. J. F.

Gems and Gem Materials. By E. H. KRAUS and C. B. SLAWSON. 5th ed. New York: McGraw-Hill Book Co., Inc., 1947. Pp. ix+332; figs. 403. $4.00.

The arrangement of the contents of this highly successful elementary book has not changed since it was first published in 1925. So many minor alterations have been made that this edition has been reset. There is now a brief bibliography, as well as a new eight-page section on "Crystal Structure and X-Ray Methods." The fine color plates taken from Eppler which were present in the third edition are missing.

D. J. F.

ERRATA

In "Deformation of Quartz Conglomerates in Central Norway," by Christoffer Oftedahl, in the September 1948 *Journal.*

p. 481, eq. (4) read $\left.\frac{a}{c}\right\}$ instead of $\left.\frac{a}{c}\right\}$

p. 486, eq. (14) read $\left.\frac{a}{c}\right\}$ instead of $\left.\frac{a}{c}\right\}$

col. 2, line 17, read *b* instead of b

p. 487, col. 1, line 8, read *b* instead of b

line 16, read *a* and *c* instead of a and c

col 2, line 3, read *b* instead of b

line 10, read *b* instead of b

line 13, read *b* instead of b

INDEX TO VOLUME 56

Adsorption on rock surfaces (Jean Verhoogen), 216
Ahrens, L. H. *The unique association of thallium and rubidium in minerals*, 578
Alaska, eastern, Cave-in lakes in the Nabesna, Chisana, and Tanana River valleys (Robert E. Wallace), 171
  orogenic history of (A. J. Eardley), 409
  stratigraphy of, 412
Alluvial deposits, Fine-grained, and their effects on Mississippi River activity. By Harold N. Fisk. Review by A. L. Kidwell, 591
American Mississippian ammonoid zones (abstr.) (A. K. Miller), 352
Ammonoid zones, American Mississippian (abstr.) (A. K. Miller), 352
Amphibian, embolomerous, A new species of, from the Permian of Oklahoma (J. Willis Stovall), 75
Anderson, B. W. Gem testing. Review by D. Jerome Fisher, 594
Anhydrites, lead in limestones and (Frans E. Wickman), 63
  strontium in limestones and, 61
Antarctic ice specimens, The preservation of (Arthur David Howard), 67
Antevs, Ernst. Review of: Pollen profile from a Texas bog. By J. E. Potzger and B. C. Tharp, 83
Aplite and pegmatite dikes and veins in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of emplacement, The form and structural features of (B. C. King), 459
Appalachian region, central and northern, Status of Mississippian stratigraphy in the (Byron N. Cooper), 255
Appalachians, southern, Some problems in Mississippian stratigraphy of the (Paris B. Stockdale), 264
Arctic, Archipelago (A. J. Eardley), 421
  petroleum possibilities in the, 434
Arctica, Ancient (A. J. Eardley), 409
  paleontologic significance of, 433
Arkose series of sediments (Paul D. Krynine), 153
Arnold, Chester A. An introduction to paleobotany. Review by E. C. Olson, 243
  The Mississippian flora, 367
Ash zone, Pearlette, in Missouri Valley (John C. Frye, Ada Swineford, and A. Byron Leonard), 504
Association, The unique, of thallium and rubidium in minerals (L. H. Ahrens), 578
Atherton, Elwood, and David H. Swann. *Subsurface correlations of lower Chester strata of the Eastern Interior Basin*, 269
Auckland, New Zealand, Unusual volcanic dike and grooved lava at (J. A. Bartrum and E. J. Searle), 226

Backlund, H. G. On granite and gneiss and the age of the earth. Review by Tom. F. W. Barth, 235
Balk, Robert. Review of: 1945 reference report on certain oil and gas fields of north Louisiana, south Arkansas, Mississippi and Alabama, 496
  Review of: Some structural features of the intrusions in the Iron Springs district. By J. H. Mackin, 245
Barth, Tom. F. W. *The distribution of oxygen in the lithosphere*, 41
  Oxygen in rocks: a basis for petrographic correlations, 50
  Petrological notes and reviews: Recent contributions to the granite problem, 235
  Review of: Eruptive rocks: their genesis, composition, classification, and their relation to ore deposits, with a chapter on meteorites. By S. J. Shand, 593
  Review of: Über die Entstehung des Granits. By M. Reinhard, 238
  Review of: Géologie du granite. By E. Raguin, 238
  Review of: On granite and gneiss and the age of the earth. By H. G. Backlund, 235
  Review of: Le Granite et les réactions à l'état solide. By R. Perrin and M. Roubault, 236
  Review of: Igneous minerals and rocks. By Ernest E. Wahlstrom, 241
  Review of: Die leukogranitischen, trondhjemitischen und leukosyenitischen Magmen und die Anatexis. By P. Niggli, 237
  Review of: Das Problem der Granitbildung. By P. Niggli, 237
  Review of: Rocks and rock minerals. By Louis V. Pirsson and Adolph Knopf, 242
Bartrum, J. A., and E. J. Searle. *Unusual volcanic dike and grooved lava from Auckland, New Zealand*, 226
Beach cusps, The formation of (Ph. H. Kuenen), 34
Bennett, Hugh Hammond. Elements of soil conservation. Review by Leland Horberg, 84
Big Horn Mountains, Wyoming, Early Tertiary fanglomerate (Robert P. Sharp), 1
  geological setting, 2
Bighorn Basin, Field conference in the: guidebook. Review by R. T. Chamberlin, 250
Black Hills terrace gravels: a study in sediment transport (William J. Plumley), 526
Blancan, problems of the, in the central Great Plains (John C. Frye, Ada Swineford, and A. Byron Leonard), 519
Blastoids from North America and Europe (Raymond C. Moore), 384
Bonneville Basin, An early report of ancient lakes in the (Ronald L. Ives), 79
Boundary problems, Mississippian-Pennsylvanian, in the Rocky Mountain region (James Steele Williams), 327
Brachiopods from North America and Europe (Raymond C. Moore), 394
Bridge, land, across Nebraska in Mississippian time, The possibility of a (E. C. Reed), 308

British Isles, Tournaisian-Viséan break in the (L. R. Laudon), 300
Brown, Harrison, and Claire Patterson. *The composition of meteoritic matter. III. Phase equilibria, genetic relationships, and planet structure*, 85
Bryozoans from North America and Europe (Raymond C. Moore), 392

Calculator, A stereographic (Robert E. Wallace), 488
Carbon, terrestrial, A note on the original isotopic composition of (Kalervo Rankama), 199
Cave-in lakes in the Nabesna, Chisana, and Tanana River valleys, eastern Alaska (Robert E. Wallace), 171
  cross section of, 174
  distribution of, 172
  origin of, 179
  recession of banks of, 178
  sequence of development of, 175
Celebes, Geological explorations in the Island of, under the leadership of H. A. Brouwer. Review by A. F. Hagner, 591
Cephalopods from North America and Europe (Raymond C. Moore), 396
Chamberlin, R. T. Review of: Field conference in the Bighorn Basin: guidebook, 250
  Review of: Le Congo physique. By Maurice Robert, 247
  Review of: A Yanqui in Patagonia. By Bailey Willis, 247
Channel conglomerates, Permian, in Texas (Everett Claire Olson), 190
Chappars, M. S. Review of: Biography of the earth. By George Gamow, 593
  Review of: Papers from the Geological Department, Glasgow University, 496
Chemical rocks (Paul D. Krynine), 155
Chemical stability, Radial diffusion and, in the gravitational field (Hans Ramberg), 448
Chemistry of thallium (L. H. Ahrens), 578
Chester strata, lower, of the Eastern Interior Basin, Subsurface correlations of (David H. Swann and Elwood Atherton), 269
Chisana, Nabesna, and Tanana River valleys, eastern Alaska, Cave-in lakes in the (Robert E. Wallace), 171
Classification, field, The megascopic study and, of sedimentary rocks (Paul D. Krynine), 130
  of sedimentary rocks, A (Robert R. Shrock), 118
  of the sedimentary rocks, A preface to the (F. J. Pettijohn), 112
Coals (Robert R. Shrock), 125
Colorado, central, Guide to the geology of. Review by A. F. Hagner, 592
Color of sediments (Paul D. Krynine), 143
Composition, original isotopic, of terrestrial carbon, A note on the (Kalervo Rankama), 199
  of sediments (Paul D. Krynine), 132
Compound $CaO \cdot 2Al_2O_3$, The (Julian R. Goldsmith), 80
Concretions, Hollow ferruginous, in South Carolina (Laurence L. Smith), 218
  composition and form of, 219
  features controlling growth and shapes of, 223
  loci and mode of deposition of, 222
  origin of, 220
Condra, G. E., E. C. Reed, and E. D. Gordon. Correlation of Pleistocene deposits of Nebraska. Review by Leland Horberg, 496
Conglomerates (Robert R. Shrock), 120
  quartz, in central Norway, Deformation of (Christoffer Oftedahl), 476
Congo physique, Le. By Maurice Robert. Review by R. T. Chamberlin, 247
Conodonts, Kinderhook (Chalmer L. Cooper), 361
Cooper, Byron N. *Status of Mississippian stratigraphy in the central and northern Appalachian region*, 255
Cooper, Chalmer L. *Kinderhook micropaleontology*, 353
Corals from North America and Europe (Raymond C. Moore), 379
Correlation, Introduction to symposium on problems of Mississippian stratigraphy and (J. Marvin Weller), 253
  of Pleistocene deposits of the central Great Plains with the glacial section (John C. Frye, Ada Swineford, and A. Byron Leonard), 501
Correlations, Subsurface, of lower Chester strata of the Eastern Interior Basin (David H. Swann and Elwood Atherton), 269
Craters and crater springs of the Rio Salado (E. R. Harrington), 182
Crinoids from North America and Europe (Raymond C. Moore), 385
Crystallization (Jean Verhoogen), 213
Crystallography, An introduction to. By F. C. Phillips. Review by D. Jerome Fisher, 167
Cusps, beach, The formation of (Ph. H. Kuenen), 34
  origin of, 34
  spacing of, 37
Cycle, inorganic, of oxygen (Tom. F. W. Barth), 48

Deformation of quartz conglomerates in central Norway (Christoffer Oftedahl), 476
Depth relations of Fe_2O_3, Fe_3O_4, FeO, and iron, The (Tom. F. W. Barth), 43
Diabase-hornblende minette (Tom. F. W. Barth), 55
Diffusion, Radial, and chemical stability in the gravitational field (Hans Ramberg), 448
Dike, Unusual volcanic, and grooved lava at Auckland, New Zealand (J. A. Bartrum and E. J. Searle), 226
Dikes and veins, aplite and pegmatite, in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of emplacement, The form and structural features of (B. C. King), 459
Distribution of oxygen in the lithosphere, The (Tom. F. W. Barth), 41
Dolostones (Robert R. Shrock), 126
Drainage patterns in the Black Hills region (William J. Plumley), 538

Eardley, A. J. *Ancient Arctica*, 409
Early Tertiary fanglomerate, Big Horn Mountains, Wyoming (Robert P. Sharp), 1
Earth, Biography of the. By George Gamow. Review by M. S. Chappars, 593
Earth quakes, When the. By James B. Macelwane. Review by M. King Hubbert, 245
Earthquakes in the north Japan and Manchuria region, On seismogram types and focal depth of. By Eijo Vesanen. Review by M. King Hubbert, 248

Earth's crust, abundance of thallium in (L. H. Ahrens), 589
Eastern Interior Basin, Subsurface correlations of lower Chester strata of the (David H. Swann and Elwood Atherton), 269
Echinoids from North America and Europe (Raymond C. Moore), 392
Ecology, problems in, in Rocky Mountain region (James Steele Williams), 348
Ekblaw, George E., M. M. Leighton, and Leland Horberg. *Physiographic divisions of Illinois*, 16
Elements of soil conservation. By Hugh Hammond Bennett. Review by Leland Horberg, 84
Embolomerous amphibian from the Permian of Oklahoma, A new species of (J. Willis Stovall), 75
Emplacement, The form and structural features of aplite and pegmatite dikes and veins in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of (B. C. King), 459
Eruptive rocks: their genesis, composition, classification, and their relation to ore deposits, with a chapter on meteorites. By S. J. Shand. Review by D. Jerome Fisher, 593
Europe, North America and, Paleontological features of Mississippian rocks in (Raymond C. Moore), 373

Facies, and lithology of the Osage (Erwin L. Selk), 305
in Mississippian of Appalachian region (Byron N. Cooper), 259
Fanglomerate, Early Tertiary, Big Horn Mountains, Wyoming (Robert P. Sharp), 1
Fanning, Leonard M. American oil operations abroad. Review by H. W. Straley III, 168
Fauna, molluscan, of Pearlette volcanic ash (John C. Frye, Ada Swineford, and A. Byron Leonard), 514
Ferruginous concretions, Hollow, in South Carolina (Laurence L. Smith), 218
Field classification, The megascopic study and, of sedimentary rocks (Paul D. Krynine), 130
Fisher, D. Jerome. Review of: An introduction to crystallography. By F. C. Phillips, 167
Review of: Gem testing. By B. W. Anderson, 594
Review of: Gems and gem materials. By E. H. Kraus and C. B. Slawson, 594
Review of: The pegmatites of central Nigeria. By R. Jacobson and J. S. Webb, 246
Fisk, Harold N. Fine-grained alluvial deposits and their effects on Mississippi River activity. Review by A. L. Kidwell, 591
Flora, The Mississippian (Chester A. Arnold), 367
of Permian deposits in Texas (Everett Claire Olson), 197
Foraminifera, Kinderhook (Chalmer L. Cooper), 363
Foraminifers, from North America and Europe (Raymond C. Moore), 378
Formation of beach cusps, The (Ph. H. Kuenen), 34
Fragmental sedimentary rocks (Robert R. Shrock), 120
Frye, John C., Ada Swineford, and A. Byron Leonard. *Correlation of Pleistocene deposits of the central Great Plains with the glacial section*, 501

Gamow, George. Biography of the earth. Review by M. S. Chappars, 593
Gastropods from North America and Europe (Raymond C. Moore), 394
Gehlenite, the possibility of a calcium-aluminate solid solution in (Julian R. Goldsmith), 444
Gem testing. By B. W. Anderson. Review by D. Jerome Fisher, 594
Gems and gem materials. By E. H. Kraus and C. B. Slawson. Review by D. Jerome Fisher, 594
Geochemistry. *The composition of meteoritic matter. III. Phase equilibria, genetic relationships, and planet structure* (Harrison Brown and Claire Patterson), 85
The distribution of oxygen in the lithosphere (Tom. F. W. Barth), 41
Isotope ratios: a clue to the age of certain marine sediments (Frans E. Wickman), 61
A note on the original isotopic composition of terrestrial carbon (Kalervo Rankama), 199
Oxygen in rocks: a basis for petrographic calculations (Tom. F. W. Barth), 50
Radial diffusion and chemical stability in the gravitational field (Hans Ramberg), 448
The unique association of thallium and rubidium in minerals (L. H. Ahrens), 578
Geographical research, Aids to. By John Kirtland Wright and Elizabeth T. Platt. Review by Leland Horberg, 495
Geomorphology. *Ancient Arctica* (A. J. Eardley), 409
Cave-in lakes in the Nabesna, Chisana, and Tanana River valleys, eastern Alaska (Robert E. Wallace), 171
Early Tertiary fanglomerate, Big Horn Mountains, Wyoming (Robert P. Sharp), 1
Geophysics. *Geological significance of surface tension* (Jean Verhoogen), 210
Glacial section, Correlation of Pleistocene deposits of the central Great Plains with the (John C. Frye, Ada Swineford, and A. Byron Leonard), 501
Glacier, alpine, The temperature, melt water movement and density increase in the névé of an. By T. P. Hughes and Gerald Seligman. Review by Robert P. Sharp, 498
crystals, Growth of. By Gerald Seligman. Review by Robert P. Sharp, 498
flow, Mechanism of. By M. F. Perutz. Review by Robert P. Sharp, 498
structure and the mechanism of glacier flow, A crystallographic investigation of. By M. F. Perutz and Gerald Seligman. Review by Robert P. Sharp, 498
temperate, The structure of a. By Gerald Seligman. Review by Robert P. Sharp, 498
Glaciological work of the British Jungfraujoch research party. Review by Robert P. Sharp, 498
Glaessner, Martin F. Principles of micropaleontology. Review by J. Marvin Weller, 244
Glasgow University, Papers from the Geological Department. Review by M. S. Chappars, 496
Goldsmith, Julian R. *The compound $CaO \cdot 2Al_2O_3$*, 80
Some melilite solid solutions, 437
Review of: On the younger pre-Cambrian granite plutons of the Cape Province. By D. L. Scholtz, 497
Gordon, E. D., G. E. Condra, and E. C. Reed. Correlation of Pleistocene deposits of Nebraska. Review by Leland Horberg, 496

Granitbildung, Das Problem der. By P. Niggli. Review by Tom. F. W. Barth, 237
Granite, Géologie du. By E. Raguin. Review by Tom. F. W. Barth, 238
and gneiss and the age of the earth, On. By H. G. Backlund. Review by Tom. F. W. Barth, 235
problem, Recent contributions to the (Tom. F. W. Barth), 235
Le, et les réactions à l'état solide. By R. Perrin and M. Roubault. Review by Tom. F. W. Barth, 236
Granits, Über die Entstehung des. By M. Reinhard. Review by Tom. F. W. Barth, 238
Grant, Chapman. *Mima Mounds*, 229
Gravels, Black Hills terrace: a study in sediment transport (William J. Plumley), 526
Gravitational field, Radial diffusion and chemical stability in the (Hans Ramberg), 448
Graywacke series of sediments (Paul D. Krynine), 152
Great Plains, central, Correlation of Pleistocene deposits of the, with the glacial section (John C. Frye, Ada Swineford, and A. Byron Leonard), 501

Hagner, A. F. Review of: Geological explorations in the Island of Celebes under the leadership of H. A. Brouwer, 591
Review of: Guide to the geology of central Colorado, 592
Harrington, E. R. *Craters and crater springs of the Rio Salado*, 182
Holmquist's method for petrographic calculations (Tom. F. W. Barth), 53
Holopainen, Paavo E. On the gravity field and the isostatic structure of the earth's crust in the east Alps. Review by M. King Hubbert, 248
Horberg, Leland. Review of: Aids to geographical research. By John Kirtland Wright and Elizabeth T. Platt, 495
Review of: Correlation of Pleistocene deposits of Nebraska. By G. E. Condra, E. C. Reed, and E. D. Gordon, 496
Review of: Elements of soil conservation. By Hugh Hammond Bennett, 84
Review of: Outlines of the geography, life, and customs of Newfoundland-Labrador (the eastern part of the Labrador Peninsula). By V. Tanner, 495
Review of: Two problems of marine geology: atolls and canyons. By Ph. H. Kuenen, 249
M. M. Leighton, and George E. Ekblaw. *Physiographic divisions of Illinois*, 16
Howard, Arthur David. *The preservation of Antarctic ice specimens*, 67
Hubbert, M. King. Review of: When the earth quakes. By James B. Macelwane, 245
Review of: On the gravity field and the isostatic structure of the earth's crust in the east Alps. By Paavo E. Holopainen, 248
Review of: On seismogram types and focal depth of earthquakes in the north Japan and Manchuria region. By Eijo Vesanen, 248
Hughes, T. P., and Gerald Seligman. The temperature, melt water movement and density increase in the névé of an alpine glacier. Review by Robert P. Sharp, 498

Ice specimens, Antarctic, The preservation of (Arthur David Howard), 67
Igneous minerals and rocks. By Ernest E. Wahlstrom. Review by Tom. F. W. Barth, 241
Illinois, Physiographic divisions of (M. M. Leighton, George E. Ekblaw, and Leland Horberg), 16
Coastal Plain province, 32
differences in age of the uppermost drift, 20
differences in glacial morphology, 20
Dissected Till Plains section, 28
extent of the several glaciations, 20
general description and regional relations, 16
glaciofluvial aggradation of a basin area, 21
glaciolacustrine action, 21
Great Lake section, 21
height above main lines of drainage, 21
Interior Low Plateaus province, 31
Ozark Plateaus province, 29
Till Plains section, 24
topography of the bedrock surface, 17
Wisconsin Driftless section, 28
Intrusives in Osi area of Nigeria (B. C. King), 459
Ironstones (Robert R. Shrock), 125
Isostatic structure of the earth's crust in the east Alps, On the gravity field and the. By Paavo E. Holopainen. Review by M. King Hubbert, 248
Isotope ratios: a clue to the age of certain marine sediments (Frans E. Wickman), 61
Isotopes, carbon, astrophysical and geological background of the fractionation of (Kalervo Rankama), 199
terrestrial and meteoritic abundance of, 202
Isotopic composition, original, of terrestrial carbon, A note on the (Kalervo Rankama), 199
Ives, Ronald L. *An early report of ancient lakes in the Bonneville Basin*, 79

Jacobson, R., and J. S. Webb. The pegmatites of central Nigeria. Review by D. Jerome Fisher, 246

Kidwell, A. L. Review of: Fine-grained alluvial deposits and their effects on Mississippi River activity. By Harold N. Fisk, 591
Kinderhook micropaleontology (Chalmer L. Cooper), 353
King, B. C. *The form and structural features of aplite and pegmatite dikes and veins in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of emplacement*, 459
Knopf, Adolph, and Louis V. Pirsson. Rocks and rock minerals. Review by Tom. F. W. Barth, 242
Kraus, E. H., and C. B. Slawson. Gems and gem materials. Review by D. Jerome Fisher, 594
Krynine, Paul D. *The megascopic study and field classification of sedimentary rocks*, 130
Kuenen, Ph. H. *The formation of beach cusps*, 34
Two problems of marine geology: atolls and canyons. Review by Leland Horberg, 249

Lakes, ancient, in the Bonneville Basin, An early report of (Ronald L. Ives), 79
Cave-in, in the Nabesna, Chisana, and Tanana River valleys, eastern Alaska (Robert E. Wallace), 171

Laudon, L. R. *Osage-Meramec contact*, 288
Lava, grooved, Unusual volcanic dike and, at Auckland, New Zealand (J. A. Bartrum and E. J. Searle), 226
Leighton, M. M., George E. Ekblaw, and Leland Horberg. *Physiographic divisions of Illinois*, 16
Leonard, A. Byron, John C. Frye, and Ada Swineford. *Correlation of Pleistocene deposits of the central Great Plains with the glacial section*, 501
Limestones (Robert R. Shrock), 126
and anhydrites, lead in (Frans E. Wickman), 63
and anhydrites, strontium in, 61
with high content of uranium, 65
Lithology, facies and, of the Osage (Erwin L. Selk), 305
Lithosphere, The distribution of oxygen in the (Tom. F. W. Barth), 41
Lund, Lars. *Determination of sodium and potassium in silicate minerals and rocks*, 490

Macelwane, James B. When the earth quakes. Review by M. King Hubbert, 245
Mackin, J. H. Some structural features of the intrusions in the Iron Springs district. Review by R. Balk, 245
McLaughlin, Kenneth P. *Secondary tilt: a review and a new solution*, 72
Magmen, Die leukogranitischen, trondhjemitischen und leukosyenitischen, und die Anatexis. By P. Niggli. Review by Tom. F. W. Barth, 237
Marine geology, Two problems of: atolls and canyons. By Ph. H. Keunen. Review by Leland Horberg, 249
Maturity, indices of, in sediments (William J. Plumley), 571
"Mayes" in Oklahoma, Problem of the (Erwin L. Selk), 303
Megascopic study and field classification of sedimentary rocks, The (Paul D. Krynine), 130
Melilite solid solutions, Some (Julian R. Goldsmith), 437
Melilites, soda content of (Julian R. Goldsmith), 438
Meramec, Osage-, contact (L. R. Laudon), 288
Meteorites, abundance studies of isotopes based on (Kalervo Rankama), 208
Meteoritic matter, The composition of. III. Phase equilibria, genetic relationships, and planet structure (Harrison Brown and Claire Patterson), 85
Micropaleontology, Kinderhook (Chalmer L. Cooper), 353
Principles of. By Martin F. Glaessner. Review by J. Marvin Weller, 244
Miller, A. K. *American Mississippian ammonoid zones* (abstr.), 352
Mima Mounds (Chapman Grant), 229
A reply (Victor B. Scheffer), 231
Minerals, The unique association of thallium and rubidium in (L. H. Ahrens), 578
Mississippian, American, ammonoid zones (abstr.) (A. K. Miller), 352
flora, The (Chester A. Arnold), 367
Kinderhook micropaleontology (Chalmer L. Cooper), 353
Osage-Meramec contact (L. R. Laudon), 288
-Pennsylvanian boundary problems in the Rocky Mountain region (James Steele Williams), 327
Problem of the "Mayes" in Oklahoma (Erwin L. Selk), 303
rocks in North America and Europe, Paleontological features of (Raymond C. Moore), 373
stratigraphy in the central and northern Appalachian region, Status of (Byron N. Cooper), 255
stratigraphy and correlation, Introduction to symposium on problems of (J. Marvin Weller), 253
stratigraphy of the southern Appalachians, Some problems in (Paris B. Stockdale), 264
stratigraphy in southwestern United States, Some problems of (Alexander Stoyanow), 313
Subsurface correlations of lower Chester strata of the Eastern Interior Basin (David H. Swann and Elwood Atherton), 269
time, The possibility of a land bridge across Nebraska in (E. C. Reed), 308
Moncrief gravel, age of the (Robert P. Sharp), 11
distribution, 6
lithology and constitution, 5
origin of the, 12
stratigraphic and structural relations, with the Kingsbury conglomerate, 8
stratigraphic and structural relations, with the pre-Tertiary rocks, 10
stratigraphic and structural relations, with the "Wasatch," 7
thickness, 6
Moore, Raymond C. *Paleontological features of Mississippian rocks in North America and Europe*, 373

Nabesna, Chisana, and Tanana River valleys, eastern Alaska, Cave-in lakes in the (Robert E. Wallace), 171
Nebraska, The possibility of a land bridge across, in Mississippian time (E. C. Reed), 308
New Mexico. *Craters and crater springs of the Rio Salado* (E. R. Harrington), 182
New Zealand, Unusual volcanic dike and grooved lava at Auckland (J. A. Bartrum and E. J. Searle), 226
Newfoundland-Labrador (the eastern part of the Labrador Peninsula), Outlines of the geography, life, and customs of. By V. Tanner. Review by Leland Horberg, 495
Nigeria, northern provinces of, The form and structural features of aplite and pegmatite dikes and veins in the Osi area of the, and the criteria that indicate a nondilational mode of emplacement (B. C. King), 459
Niggli, P. Die leukogranitischen, trondhjemitischen und leukosyenitischen Magmen und die Anatexis. Review by Tom. F. W. Barth, 237
Das Problem der Granitbildung. Review by Tom. F. W. Barth, 237
Niggli's method in petrographic calculations (Tom. F. W. Barth), 51
North America and Europe, Paleontological features of Mississippian rocks in (Raymond C. Moore), 373
Norway, central, Deformation of quartz conglomerates in (Christoffer Oftedahl), 476

Oftedahl, Christoffer. *Deformation of quartz conglomerates in central Norway*, 476
Oil and gas fields, certain, of north Louisiana, south Arkansas, Mississippi and Alabama, 1945 reference report on. Review by R. Balk, 496

Oil operations abroad, American. By Leonard M. Fanning. Review by H. W. Straley III, 168
Oklahoma, A new species of embolomerous amphibian from the Permian of (J. Willis Stovall), 75
Problem of the "Mayes" in (Erwin L. Selk), 303
Olson, Everett Claire. *A preliminary report on vertebrates from the Permian Vale formation of Texas*, 186
Review of: An introduction to paleobotany. By Chester A. Arnold, 243
Review of: Outlines of paleontology. By H. H. Swinnerton, 243
Orogeny. *Ancient Arctica* (A. J. Eardley), 409
Osage, facies and lithology of (Erwin L. Selk), 305
-Meramec contact (L. R. Laudon), 288
Osi area of the northern provinces of Nigeria, The form and structural features of aplite and pegmatite dikes and veins of the, and the criteria that indicate a nondilational mode of emplacement (B. C. King), 459
Ostracodes, Kinderhook (Chalmer L. Cooper), 362
Oxygen, in the lithosphere, The distribution of (Tom. F. W. Barth), 41
the inorganic cycle of, 48
and the rock-forming minerals, 51
in rocks: a basis for petrographic calculations, 50
the volume relations of, in the lithosphere, 41

Paleobotany, An introduction to. By Chester A. Arnold. Review by E. C. Olson, 243
The Mississippian flora (Chester A. Arnold), 367
Paleogeographic problems, in southwestern United States (Alexander Stoyanow), 322
Paleogeography, problems in, in the Rocky Mountain region (James Steele Williams), 348
Paleontologic significance of Ancient Arctica (A. J. Eardley), 433
Paleontological features of Mississippian rocks in North America and Europe (Raymond C. Moore), 373
Paleontology, invertebrate, Mississippian (L. R. Laudon), 298
invertebrate, of Mississippian in southwestern United States (Alexander Stoyanow), 317
Outlines of. By H. H. Swinnerton. Review by E. C. Olson, 243
problems in, in Rocky Mountain region (James Steele Williams), 340
vertebrate. *A new species of embolomerous amphibian from the Permian of Oklahoma* (J. Willis Stovall), 75
vertebrate. *A preliminary report on vertebrates from the Permian Vale formation of Texas* (Everett Claire Olson), 186
Paleophysiography in Great Plains (John C. Frye, Ada Swineford, and A. Byron Leonard), 517
Patagonia, A Yanqui in. By Bailey Willis. Review by R. T. Chamberlin, 247
Patterson, Claire, and Harrison Brown. *The composition of meteoritic matter. III. Phase equilibria, genetic relationships, and planet structure*, 85
Pearlette ash zone in Missouri Valley (John C. Frye, Ada Swineford, and A. Byron Leonard), 504
Pegmatite, aplite and, dikes and veins in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of emplacement, The form and structural features of (B. C. King), 459
Pegmatites of central Nigeria, The. By R. Jacobson and J. S. Webb. Review by D. Jerome Fisher, 246
Pelecypods from North America and Europe (Raymond C. Moore), 394
Pennsylvanian, Mississippian-, boundary problems in the Rocky Mountain region (James Steele Williams), 327
Permafrost. *Cave-in lakes in the Nabesna, Chisana, and Tanana River valleys, eastern Alaska* (Robert E. Wallace), 171
Permian, of Oklahoma, A new species of embolomerous amphibian from the (J. Willis Stovall), 75
Vale formation of Texas, A preliminary report on vertebrates from the (Everett Claire Olson), 186
Perrin, R., and M. Roubault. Le Granite et les réactions à l'état solide. Review by Tom. F. W. Barth, 236
Perutz, M. F. Mechanism of glacier flow. Review by Robert P. Sharp, 498
and Gerald Seligman. A crystallographic investigation of glacier structure and the mechanism of glacier flow. Review by Robert P. Sharp, 498
Petrographic calculations, Oxygen in rocks: a basis for (Tom. F. W. Barth), 50
Petrographic classification, of igneous rocks (Paul D. Krynine), 156
of sedimentary rocks, 157
Petrography of the Pearlette volcanic ash (John C. Frye, Ada Swineford, and A. Byron Leonard), 507
Petroleum possibilities in the Arctic (A. J. Eardley), 434
Petrological notes and reviews (Tom. F. W. Barth), 235
Petrology. *The compound* $CaO \cdot 2Al_2O_3$ (Julian R. Goldsmith), 80
Some melilite solid solutions, 437
Pettijohn, F. J. *A preface to the classification of the sedimentary rocks*, 112
Phase equilibria, genetic relationships, and planet structure. III. The composition of meteoritic matter (Harrison Brown and Claire Patterson), 85
Phillips, F. C. An introduction to crystallography. Review by D. Jerome Fisher, 167
Physiographic divisions of Illinois (M. M. Leighton, George E. Ekblaw, and Leland Horberg), 16
Physiography in Black Hills region (William J. Plumley), 526
Pirsson, Louis V., and Adolph Knopf. Rocks and rock minerals. Review by Tom. F. W. Barth, 242
Planet structure, Phase equilibria, genetic relationships, and. III. The composition of meteoritic matter (Harrison Brown and Claire Patterson), 85
Platt, Elizabeth T., and John Kirtland Wright. Aids to geographical research. Review by Leland Horberg, 495
Pleistocene deposits, of the central Great Plains, Correlation of, with the glacial section (John C. Frye, Ada Swineford, and A. Byron Leonard), 501

of Nebraska, Correlation of. By G. E. Condra, E. C. Reed, and E. D. Gordon. Review by Leland Horberg, 496
Plumley, William J. *Black Hills terrace gravels: a study in sediment transport*, 526
Plutons, younger pre-Cambrian granite, of the Cape Province, On the. By D. L. Scholtz. Review by Julian R. Goldsmith, 497
Pollen profile from a Texas bog. By J. E. Potzger and B. C. Tharp. Review by Ernst Antevs, 83
Potassium, sodium and, in silicate minerals and rocks, Determination of (Lars Lund), 490
Potzger, J. E., and B. C. Tharp. Pollen profile from a Texas bog. Review by Ernst Antevs, 83
Preservation of Antarctic ice specimens, The (Arthur David Howard), 67
Ptygmatic veins (B. C. King), 469

Quartz conglomerates in central Norway, Deformation of (Christoffer Oftedahl), 476
Quartzite series, of sediments (Paul D. Krynine), 149

Radiolarites, Shallow-water origin of, in southern Turkey (S. W. Tromp), 492
Raguin, E. Géologie du granite. Review by Tom. F. W. Barth, 238
Ramberg, Hans. *Radial diffusion and chemical stability in the gravitational field*, 448
Rankama, Kalervo. *A note on the original isotopic composition of terrestrial carbon*, 199
Reed, E. C. *The possibility of a land bridge across Nebraska in Mississippian time*, 308
G. E. Condra, and E. D. Gordon. Correlation of Pleistocene deposits of Nebraska. Review by Leland Horberg, 496
Reinhard, M. Über die Entstehung des Granits. Review by Tom. F. W. Barth, 238
Rio Salado, Craters and crater springs of the (E. R. Harrington), 182
Robert, Maurice. Le Congo physique. Review by R. T. Chamberlin, 247
Rock, the standard cell of a (Tom. F. W. Barth), 50
Rocks, Oxygen in: a basis for petrographic calculations (Tom. F. W. Barth), 50
and rock minerals. By Louis V. Pirsson and Adolph Knopf. Review by Tom. F. W. Barth, 242
Rocky Mountain region, Mississippian-Pennsylvanian boundary problems in the (James Steele Williams), 327
Roubault, M., and R. Perrin. Le Granite et les réactions à l'état solide. Review by Tom. F. W. Barth, 236
Rounding, equation of (William J. Plumley), 565
Rubidium, thallium and, in minerals, The unique association of (L. H. Ahrens), 578

Salt Range of the Punjab, Second symposium on the age of the Saline series. Review by J. Marvin Weller, 166
Sand analysis of Black Hills streams (William J. Plumley), 561
Sandstones (Robert R. Shrock), 121
Scheffer, Victor B. *Mima Mounds: a reply*, 231
Scholtz, D. L. On the younger pre-Cambrian granite plutons of the Cape Province. Review by Julian R. Goldsmith, 497
Searle, E. J., and J. A. Bartrum. *Unusual volcanic dike and grooved lava at Auckland, New Zealand*, 226
Secondary tilt: a review and a new solution (Kenneth P. McLaughlin), 72
Sediment transport, Black Hills terrace gravels: a study in (William J. Plumley), 526
Sedimentary rocks, A classification of (Robert R. Shrock), 118
The megascopic study and field classification of (Paul D. Krynine), 130
A preface to the classification of the (F. J. Pettijohn), 112
Sedimentology. *Black Hills terrace gravels: a study in sediment transport* (William J. Plumley), 526
Sediments, certain marine, Isotope ratios: a clue to the age of (Frans E. Wickman), 61
color of (Paul D. Krynine), 143
composition of, 132
makeup of, 132
petrographic classification of, 157
structure of, 145
texture of, 136
Seligman, Gerald. Growth of glacier crystals. Review by Robert P. Sharp, 498
The structure of a temperate glacier. Review by Robert P. Sharp, 498
and T. P. Hughes. The temperature, melt water movement and density increase in the névé of an alpine glacier. Review by Robert P. Sharp, 498
and M. F. Perutz. A crystallographic investigation of glacier structure and the mechanism of glacier flow. Review by Robert P. Sharp, 498
Selk, Erwin L. *Problem of the "Mayes" in Oklahoma*, 303
Shales (Robert R. Shrock), 123
and siltstones (Paul D. Krynine), 154
Shand, S. J. Eruptive rocks: their genesis, composition, classification, and their relation to ore deposits, with a chapter on meteorites. Review by Tom. F. W. Barth, 593
Sharp, Robert P. *Early Tertiary fanglomerate, Big Horn Mountains, Wyoming*, 1
Review of: A crystallographic investigation of glacier structure and the mechanism of glacier flow. By M. F. Perutz and Gerald Seligman, 498
Review of: Growth of glacier crystals. By Gerald Seligman, 498
Review of: Mechanism of glacier flow. By M. F. Perutz, 498
Review of: The structure of a temperate glacier. By Gerald Seligman, 498
Review of: The temperature, melt water movement and density increase in the névé of an alpine glacier. By T. P. Hughes and Gerald Seligman, 498
Shrock, Robert R. *A classification of sedimentary rocks*, 118
Silicastones (Robert R. Shrock), 125
Silicate minerals and rocks, Determination of sodium and potassium in (Lars Lund), 490
Slawson, C. B., and E. H. Kraus. Gems and gem materials. Review by D. Jerome Fisher, 594
Smith, Laurence L. *Hollow ferruginous concretions in South Carolina*, 218
Sodium and potassium in silicate minerals and rocks, Determination of (Lars Lund), 490

Solfataric alteration (Tom. F. W. Barth), 57
Solid solutions, Some melilite (Julian R. Goldsmith), 437
South Africa, Transactions of the Geological Society of, vol. 47. Review, 497
South Carolina, Hollow ferruginous concretions in (Laurence L. Smith), 218
South Dakota. *Black Hills terrace gravels: a study in sediment transport* (William J. Plumley), 526
Species differentiation (James Steele Williams), 341
Springs, crater, Craters and, of the Rio Salado (E. R. Harrington), 182
Stability, chemical, Radial diffusion and, in the gravitational field (Hans Ramberg), 448
Standard cell, the composition of the (Tom. F. W. Barth), 54
Stavanger area, Norway (Tom. F. W. Barth), 57
Stereographic calculator, A (Robert E. Wallace), 488
Stockdale, Paris B. *Some problems in Mississippian stratigraphy of the southern Appalachians*, 264
Stoichiometric crystals, the gravitative stability of (Hans Ramberg), 452
Stovall, J. Willis. *A new species of embolomerous amphibian from the Permian of Oklahoma*, 75
Stoyanow, Alexander. *Some problems of Mississippian stratigraphy in southwestern United States*, 313
Straley, H. W., III. Review of: American oil operations abroad. By Leonard M. Fanning, 168
Stratigraphy, of Alaska (A. J. Eardley), 412
Correlation of Pleistocene deposits of the central Great Plains with the glacial section (John C. Frye, Ada Swineford, and A. Byron Leonard), 501
Mississippian (Chalmer L. Cooper), 355
Mississippian, in the central and northern Appalachian region, Status of (Byron N. Cooper), 255
Mississippian, and correlation, Introduction to symposium on problems of (J. Marvin Weller), 253
Mississippian. *Osage-Meramec contact* (L. R. Laudon), 288
Mississippian. *Problem of the "Mayes" in Oklahoma* (Erwin L. Selk), 303
Mississippian, in Rocky Mountain region (James Steele Williams), 329
Mississippian, of the southern Appalachians, Some problems in (Paris B. Stockdale), 264
Mississippian, in southwestern United States, Some problems of (Alexander Stoyanow), 313
Mississippian. *Subsurface correlations of lower Chester strata of the Eastern Interior Basin* (David H. Swann and Elwood Atherton), 269
problems in, in Rocky Mountain region (James Steele Williams), 346
Structural features, The form and, of aplite and pegmatite dikes and veins in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of emplacement (B. C. King), 459
of the intrusions in the Iron Springs district, Some. By J. H. Mackin. Review by R. Balk, 245
Structure of sediments (Paul D. Krynine), 145
Subsurface correlations of lower Chester strata of the Eastern Interior Basin (David H. Swann and Elwood Atherton), 269
Surface tension, Geological significance of (Jean Verhoogen), 210
Swann, David H., and Elwood Atherton. *Subsurface correlations of lower Chester strata of the Eastern Interior Basin*, 269
Swineford, Ada, John C. Frye, and A. Bryon Leonard. *Correlation of Pleistocene deposits of the central Great Plains with the glacial section*, 501
Swinnerton, H. H. Outlines of paleontology. Review by E. C. Olson, 243
Symposium on problems of Mississippian stratigraphy and correlation, Introduction to (J. Marvin Weller), 253
Systemic boundaries, in Mississippian system of Appalachian region (Byron N. Cooper), 258

Tanana, Nabesna, Chisana, and, River valleys, eastern Alaska, Cave-in lakes in the (Robert E. Wallace), 171
Tanner, V. Outlines of the geography, life, and customs of Newfoundland-Labrador (the eastern part of the Labrador Peninsula). Review by Leland Horberg, 495
Techniques and methods, of correlating ash zones (John C. Frye, Ada Swineford, and A. Byron Leonard), 506
Determination of sodium and potassium in silicate minerals and rocks (Lars Lund), 490
of gravel and sand analysis (William J. Plumley), 542, 562
The preservation of Antarctic ice specimens (Arthur David Howard), 67
Secondary till: a review and a new solution (Kenneth P. McLaughlin), 72
A stereographic calculator (Robert E. Wallace), 488
Tectonics. *Deformation of quartz conglomerates in central Norway* (Christoffer Oftedahl), 476
in Osi area of Nigeria (B. C. King), 459
Tension, surface, Geological significance of (Jean Verhoogen), 210
Terrace, cycles, history of the, in the Black Hills region (William J. Plumley), 534
gravels, Black Hills: a study in sediment transport, 526
systems, description of, in Black Hills, 529
Terrestrial carbon, A note on the original isotopic composition of (Kalervo Rankama), 199
Tertiary fanglomerate, Early, Big Horn Mountains, Wyoming (Robert P. Sharp), 1
Texas, A preliminary report on vertebrates from the Permian Vale formation of (Everett Claire Olson), 186
Texture of sediments (Paul D. Krynine), 136
Thallium, abundance of, in the earth's crust (L. H. Ahrens), 589
chemistry of, 578
and rubidium in minerals, The unique association of, 578
Tharp, B. C., and J. E. Potzger. Pollen profile from a Texas bog. Review by Ernst Antevs, 83
Thermodynamic equilibrium in a field of gravitation, conditions of (Tom. F. W. Barth), 41
Tillstone (Robert R. Shrock), 124
Till, Secondary: a review and a new solution (Kenneth P. McLaughlin), 72

Tromp, S. W. *Shallow-water origin of radiolarites in southern Turkey*, 492
Turkey, southern, Shallow-water origin of radiolarites in (S. W. Tromp), 492

Unconformities in Rocky Mountain region (James Steele Williams), 347
United States, southwestern, Some problems of Mississippian stratigraphy in (Alexander Stoyanow), 313
Uranium, limestone with high content of (Frans E. Wickman), 65
Utah. *An early report of ancient lakes in the Bonneville Basin* (Ronald L. Ives), 79

Vale formation, Permian, of Texas, A preliminary report on vertebrates from the (Everett Claire Olson), 186
Vapor pressure (Jean Verhoogen), 214
Veins, dikes and, aplite and pegmatite, in the Osi area of the northern provinces of Nigeria and the criteria that indicate a nondilational mode of emplacement, The form and structural features of (B. C. King), 459
Verhoogen, Jean. *Geological significance of surface tension*, 210
Vertebrates from the Permian Vale formation of Texas, A preliminary report on (Everett Claire Olson), 186
Vesanen, Eijo. On seismogram types and focal depth of earthquakes in the north Japan and Manchuria region. Review by M. King Hubbert, 248
Volcanic dike, Unusual, and grooved lava at Auckland, New Zealand (J. A. Bartrum and E. J. Searle), 226

Wahlstrom, Ernest E. Igneous minerals and rocks. Review by Tom. F. W. Barth, 241
Wallace, Robert E. *Cave-in lakes in the Nabesna, Chisana, and Tanana River valleys, eastern Alaska*, 171
A stereographic calculator, 488
Warsaw problem (L. R. Laudon), 289
Webb, J. S., and R. Jacobson. The pegmatites of central Nigeria. Review by D. Jerome Fisher, 246
Weller, J. Marvin. *Introduction to symposium on problems of Mississippian stratigraphy and correlation*, 253
Review of: Principles of micropaleontology. By Martin F. Glaessner, 244
Review of: Second symposium on the age of the Saline series in the Salt Range of the Punjab, 166
Wickman, Frans E. *Isotope ratios: a clue to the age of certain marine sediments*, 61
Williams, James Steele. *Mississippian-Pennsylvanian boundary problems in the Rocky Mountain region*, 327
Willis, Bailey. A Yanqui in Patagonia. Review by R. T. Chamberlin, 247
Wright, John Kirtland, and Elizabeth T. Platt. Aids to geographical research. Review by Leland Horberg, 495
Wyoming, Big Horn Mountains, Early Tertiary fanglomerate (Robert P. Sharp), 1

Zonation, of American Mississippian rocks (Raymond C. Moore), 376
of European Lower Carboniferous formations, 373
in Mississippian rocks of Rocky Mountain region (James Steele Williams), 343